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REVIEW

Biofortification versus diversification to fight micronutrient deficiencies: an interdisciplinary review

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Summary

Two plant production-based strategies – biofortification and dietary diversification – have been advocated to overcome micronutrient deficiencies, which are major contributors to morbidity and mortality worldwide. The respective benefits and effectiveness of these two strategies are the subject of controversy. Expanding the scope of this debate beyond the sole nutritional outcomes, and using a food system approach, this interdisciplinary review aims to providing a novel and holistic perspective on the ongoing debate. The literature shows that biofortification can be an effective medium-term strategy to tackle nutritional risk in vulnerable populations in some contexts, but that it also may have negative environmental, economic, and social impacts. Dietary diversification, on the other hand, is known to be a sustainable way to overcome micronutrient deficiencies, bringing with it long-term benefits, including nutritional, and beyond, the provision of ecosystem services. Dietary diversification is however challenging to implement, with benefits that are not immediate. Biodiversity as a basis of human diets is critically important to improving both human and environmental health. Diet diversification through increased mobilisation of biodiversity in food systems deserves much more attention and support in policies for food and nutrition in low- and middle-income countries.

Keywords Biofortification · Diet diversification · Micronutrient deficiencies · Malnutrition · Food systems

1 Introduction

Vitamins and minerals are essential to adequate nutrition. Subclinical micronutrient deficiencies, often referred to as hidden hunger (Maberly et al., 1994; Messer, 1992), increase both morbidity and mortality risks (Bailey et al., 2015). While the claim that 2 billion people worldwide are affected by micronutrient deficiencies has been made for over 30 years, a recent study suggested that this figure may actually be underestimated (Stevens et al., 2022). Along with undernutrition, overweight, obesity, and diet-related noncommunicable diseases, micronutrient deficiencies are part of the triple burden of malnutrition that undermines the opportunities and futures of individuals, as well as the prospect of achieving sustainable development for all. Since 1992, different strategies and policy recommendations to address micronutrient deficiencies have been issued by WHO and FAO (the World Health Organisation and Food and Agriculture Organisation of the United Nations, respectively; 1992, 2006). Among the recommended strategies, biofortification and dietary diversification are both food-based strategies to improve nutrition. However, the respective efficiency and sustainability of the two strategies are still subject of controversy among scientists and policy makers. The two strategies follow quite different agricultural development pathways, they involve different actors, lobbies,

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agricultural practices, and ultimately, they imply stark differences in their underpinning visions regarding the role of agriculture in society (Fig. 1).

The aim of biofortification is to increase the nutritional density of vitamins and minerals in the edible part of the plants. Major staple crops are the main targets for biofortification. Biofortification may also aim to enhance food utilisation by improving nutrient bioavailability (Thompson & Amoroso, 2014). Biofortification initially focused on iron (Fe), zinc (Zn), and provitamin A because of their frequent inadequate dietary intakes in poor rural households and their negative health outcomes, notably anaemia, blindness, impaired physical and mental development, morbidity and mortality (Bouis et al., 2011). Biofortification uses two main approaches. The first is to apply fertilisers to increase nutrient uptake from the soil or via foliar applications, and improve the accumulation conditions in the edible parts of plants (Hirschi, 2009). Agronomic biofortification has been shown to increase the concentration of micronutrients including that of Fe, Zn and selenium (Se) in rice, wheat, corn, barley, sorghum, potato, soybean, and other legumes, and in vegetables including carrots, onion, and garlic (Fang et al., 2008; Phattarakul et al., 2012; Wang et al., 2012). The second approach entails the insertion of biofortified plant varieties that accumulate higher levels of micronutrients in cropping systems. In the case of the main cereal crops used in intensive agriculture, this approach aims to address the limited micronutrient contents in varieties resulting from decades of breeding specifically aimed at increasing yields and amplified by climate change (Leisner, 2020). Different varieties of key food crops including rice, wheat, corn, barley, potato, tomato, and pulses have been biofortified with Fe, Zn, and vitamin A worldwide (Cakmak et al., 2017; Garg et al., 2018). These varieties are the result of conventional breeding (Saltzman et al., 2013), genetic engineering, and genome editing technologies (Garg et al., 2018).

Whereas biofortification focuses on one or a few nutrients at a time, dietary diversification considers a spectrum of micronutrients supplied through the consumption of a sufficient variety of foods. These include plant (fruit, vegetables, cereals, and legumes), and animal products (meat, or products of fisheries and aquaculture). Based on the principle that no single food can provide a sufficient quantity of all the nutrients required to maintain optimal health, eating a

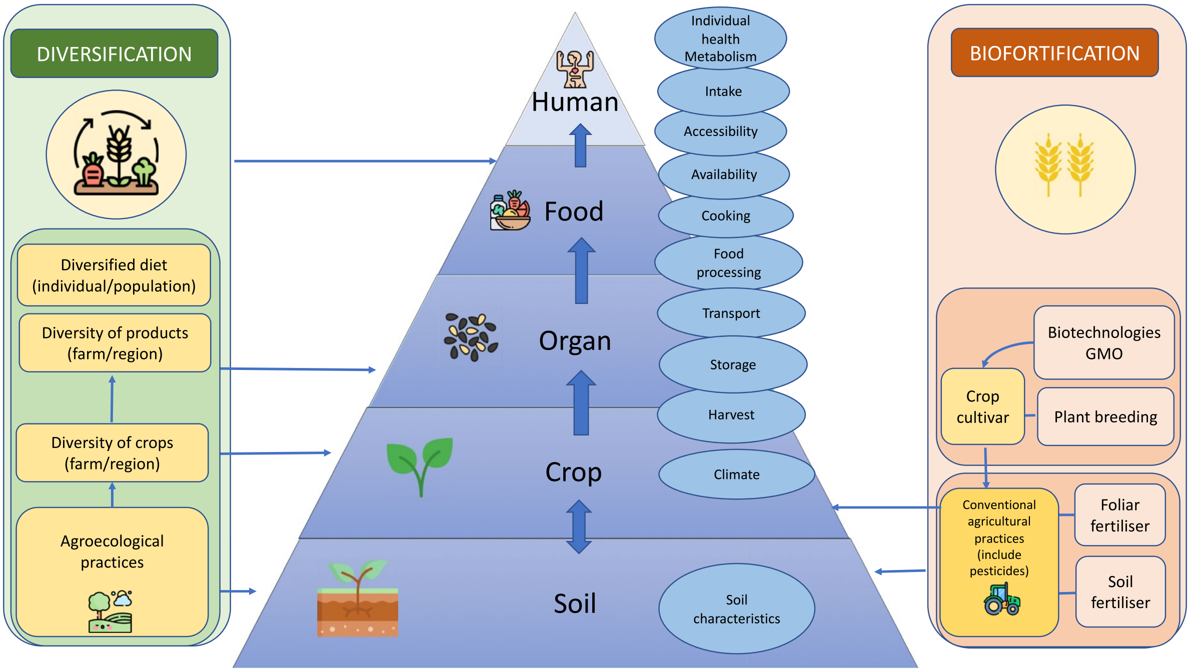


Fig. 1 Summary framework of two agricultural solutions to overcome micronutrient deficiencies: 'Biofortification' versus 'Diversification'. Reducing micronutrient deficiencies by correcting the micronutrient content of food depends on a series of steps (blue triangle and large blue arrows), from the field (bottom of the triangle) to the consumer (top). Biofortification (right hand-side, orange box) consists in increasing the micronutrient content of staple crops. This can be achieved using different approaches e.g. transgenic, marker assisted, or conventional plant breeding, and different agricultural practices, including fertilisation to increase the micronutrient content in the edible organs, combined with other chemical inputs, such as pesticides. Diversification (left, green box) acts at different steps and scales: agroecological practices (bottom) increase crop diversity at the farm and regional scales, thereby increasing the number of different farm products supplying a diversity of markets. Diversification of diets (left, top) influences micronutrient intakes. The final nutritional outcomes of both strategies depend on factors operating at the field to the consumer scales (blue ellipses). Figure 1 presents two contrasting agricultural pathways but intermediate pathways may exist: dietary diversification may co-exist within a regime of conventional agriculture, and biofortification may occur in low-input agriculture

variety of foods has been a longstanding public health recommendation worldwide.

Both biofortification and diversification are the subject of conflicting arguments and policies. On the one hand, it is argued that further breeding and transgenic programmes are required to develop new staple crop varieties capable of adapting to climate change, that produce high yields, and that are nutrient-enriched (Ofori et al., 2022). Such varieties should be grown by poor farmers using chemicals to increase the concentration of nutrients while protecting the crop against pathogens, animal pests, weeds and adverse effects of climate change (Maqbool et al., 2020). On the other hand, it also is argued that biofortification restricts nutrition to only a few nutrients; that it fails to address the root causes of undernutrition, which are linked to poverty and inequality; and that the best way to eliminate micronutrient deficiencies is to promote an increased supply and consumption of a wider range of foods (Graham et al., 2007).

Food systems are changing rapidly in low-income and middle-income countries (LMICs), in relation with growing populations and urbanisation. A food system "*gathers all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the output of these activities, including socio-economic and environmental outcomes*" (High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, 2017). Consequently, a food system approach encompasses the whole range of activities, drivers, and outcomes of a food system, their interconnections and interactions, and its actors (Ericksen, 2008; Sobal et al., 1998). Such an approach provides a more comprehensive view of the full range of consequences of any organisational choices in the food system, such as food-based strategies to improve nutrition (Tendall et al., 2015), or even the increase in risks and burdens of infectious diseases (Waage et al., 2022). In this article, we deconstruct the controversy between biofortification and diversification through an interdisciplinary prism using a food system approach. We review the results achieved by the two strategies reported in the literature through nutrition and health, agricultural, environmental, and social sciences lenses, before reconsidering the framework in a transdisciplinary perspective.

2 Biofortification versus diversification: Effects on nutrition and health

2.1 Biofortification, micronutrient intakes and status, impacts on health

The vast majority of studies on the potential of biofortification to reduce micronutrient deficiencies have focused on three main micronutrients: Zn, Fe and provitamin A (Ofori et al., 2022). It has been estimated that biofortification has the potential to improve coverage of the estimated average requirement by 25% for zinc crops, 35% for iron crops, and > 85% for provitamin A crops (Van Der Straeten et al., 2020). Recent challenges concern the development of multinutrient biofortified maize to increase the likelihood of meeting recommended intakes of macro- and micronutrients thereby reducing multiple deficiencies (Goredema-Matongera et al., 2021; Van Der Straeten et al., 2020).

Changes in micronutrient status and health outcomes of individuals enrolled in randomized trials conducted in controlled conditions are required to evaluate the nutritional efficacy of biofortified crops. The literature reports contrasting results in chidren, women and general population (Table. 1). Biofortification appears to effectively improve the micronutrient status of children (Palmer et al., 2016a, b; Scott et al., 2018) and to have some beneficial effects on eye health (Palmer et al., 2016a), cognitive function (Scott et al., 2018), and diarrhea (Jones & De Brauw, 2015). No significant effects have been shown on either the zinc or iron status and anaemia in women (Murray-Kolb et al., 2017; Sazawal et al. (2018). However, despite the lack of improvement in micronutrient status, some health benefits have been reported for cognitive performance (Murray-Kolb et al., 2017), morbidity, and a reduction in the number of days during which patients suffered from pneumonia, vomiting, and fever (Sazawal et al., 2018). In their systematic review and meta-analysis including only three randomised efficacy trials, Finkelstein et al. (2019) confirmed that the consumption of iron-biofortified crops can improve cognitive function, in terms of attention and memory. However, the authors did not observe any change in iron status, whereas the compilation of HarvestPlus biofortification trials reported an improvement in both iron status and vitamin A status (Bouis & Saltzman, 2017).

The relevance of biological indicators is often questioned in public health medicine, because each micronutrient is distributed throughout several body organs. Measuring one or two biological indicators therefore may not provide a complete picture of the nutritional effect of a single food.

The current state of play suggests that further studies are needed to: (i) assess the impact of storage, culinary, and consumption practices to ensure the nutritional advantage of biofortified crops (Van Der Straeten et al., 2020), (ii) evaluate the bioavailability of the nutrient concerned, which is influenced by a range of dietary factors (food matrix, co-existence of inhibitors and enhancers in the food and/or meal) and host (age, physio-pathological status microbiota, genetic variation), and (iii) confirm long-term health efficacy in real conditions while accounting for the variability caused by food and host factors (Ruel et al., 2018).

Table 1 Summary of studies on the nutritional impact of biofortified crops

Authors	Country	Participant characteristics	Type of study	Biofortified crops	Outcomes	Key findings
Palmer et al. (2016b)	Zambia	4- to 8-y-old children ($n = 1024$)	Cluster-randomized controlled trial	Provitamin A carotenoid–biofortified maize meal	Vitamin A status and deficiency	Increase in serum β-carotene concentrations No effect on serum retinol and deficiency prevalence
Palmer et al. (2016a)	Zambia	4- to 8-y-old children ($n = 1024$)	Cluster-randomized controlled trial	Provitamin A carotenoid–biofortified maize	Pupillary response	Improvement in pupillary responsiveness among children with marginal or deficient vitamin A status No effect on pupillary threshold or night blindness
Scott et al. (2018)	India	Boys and girls (12 to 16 years) 6 months ($n = 140$)	Double-blind, randomized, intervention study	Iron-biofortified pearl millet	Hemoglobin, ferritin, transferrin receptor, body iron Cognitive function	Improvements in iron intakes, ferritin, transferrin receptor, body iron Improvement in attention, memory and reaction time
Jones and De Brauw (2015)	Mozambique	Children under 5-y-old ($n = 1321$)	Cluster-randomized	Provitamin A orange sweet potatoes	Prevalence and duration of diarrhea	Reduction in diarrhea prevalence and duration
Murray-Kolb et al. (2017)	Rwanda	Women aged 18–27 y with low iron status 18 weeks ($n = 150$)	Double-blind, randomized intervention	Iron biofortified beans	Iron status (hemoglobin, ferritin, transferrin receptor, body iron) Cognitive performance	No significant difference in hemoglobin and transferrin receptor concentration Positive effect on cognitive performance (speed of spatial selective attention, specificity of memory retrieval)
Sazawal et al. (2018)	India	Women of childbearing age and child pairs 6 months ($n = 6005$)	Community based, double-masked randomized controlled trial	High zinc biofortified wheat flour	Plasma zinc status Morbidity Other diseases	No significant difference in zinc concentration Positive impact on self-reported morbidity Significant reduction in days with pneumonia, vomiting in children and fever in women of childbearing age
Finkelstein et al. (2019)	Philippines India Rwanda	General population (including pregnant or lactating women)	Systematic review and meta-analysis	Rice, pearl millet, and beans iron biofortified	Iron status (hemoglobin, serum ferritin, transferrin receptor, total body iron) Cognitive function	No significant effects on iron deficiency and anemia Improvement in cognitive performance (attention, memory) More beneficial effect on cognition in subjects suffering from iron deficiency at inclusion

n = number of participants involved in clinical trials

2.2 Dietary diversification

There is strong evidence in LMICs that diets that are mainly based on starchy staples with low consumption of fruits, vegetables, and animal-sourced products are associated with inadequate intakes of essential nutrients (Ruel, 2003). A recent review summarised evidence linking dietary diversity and dietary adequacy in adolescents and adults (Verger et al., 2021). Fifty studies reported that higher dietary diversity was positively associated with the nutritional adequacy of the diet in most cases, regardless of the economic context. Further, several studies in LMICs showed that higher dietary diversity was associated with reduced risk of micronutrient deficiencies: lower odds of vitamin A insufficiency resulting from consumption of meat, poultry, fish, fruit, and vegetables in Kenyan women of reproductive age (Fujita et al., 2012). Similarly, lower odds of Zn deficiency were achieved as a result of consumption of animal source foods in Ethiopian women of reproductive age (Gebremedhin et al., 2011); and reduced odds of insufficient Zn status resulted from consumption of meat, poultry, and fish in Mozambican adolescents (Korkalo et al., 2017). However, evidence that dietary diversity has a protective effect against anaemia in women of reproductive age in LMICs is conflicting: seven articles report association between higher dietary diversity with reduced odds of anaemia, whereas five report no association (Savy et al., 2006).

While there is consistent evidence that higher dietary diversity can prevent undernourishment in LMICs, as demonstrated in Burkina Faso (Lourme-Ruiz et al., 2021), the association between higher dietary diversity with body weight (insufficient or excessive), or with the risk of non-communicable diseases was found to be inconsistent in both adolescents and adults (Verger et al., 2021). However, evidence exists for a protective role of dietary diversity against some health outcomes (e.g. cardiovascular diseases) but not for others (e.g., type 2 diabetes; Mozaffari et al., 2021, 2022).

3 Biofortification versus diversification: Effects of nutritional strategies on the Agri-food system and the environment

3.1 Biofortification and Agri-food systems

All over the world, crop breeding programmes have always invested most efforts into increasing grain yields and producing more crops to increase land productivity, improve farmers' incomes and ultimately meet the demand of the ever-increasing human population. During the first Green Revolution, the developing world witnessed an extraordinary period of increased food crop productivity, with the tripling of cereal crop productivity, with only a 30% increase in the surface area of cultivated land (Pingali, 2012). Over this period, the new varieties developed by international agricultural research centers in collaboration with national research programs have contributed to these large increases in crop productivity, although productivity gains and adoption have been uneven across crops and regions (Evenson & Gollin, 2003). Many staple crop species (not only cereals) today produce grains that are deficient in micronutrients, because of a negative correlation between (for cereals) grain weight, yield, and nutritional quality (Lata-Tenesaca et al., 2023; Mohan et al., 2023). To give but one example, wheat yields have more than doubled in many regions since the 1960s due to advances in plant breeding techniques and agronomy (Fischer et al., 2010; Grassini et al., 2013), however, the process has been accompanied by a decrease in concentration of Zn and Fe in the grains (Fan et al., 2008; Miner et al., 2022).

By the 1980s, the main objective was to adjust global food production to the growing demand for food by eliminating obstacles to crop production, particularly pests and diseases. Breeding to feed the world during the Green Revolution paved the way for the first period of GMOs in plant sciences (Buiatti et al., 2013). In contrast to the Green Revolution, the push for GMOs was based largely on private agricultural research, with varieties provided to farmers on market terms (Pingali & Raney, 2005). Increasing yields and consequently increasing the global food production (not uptake of micronutrients) was the first objective (Jacobsen et al., 2013). In this sense, biofortification is an attempt to reverse this tendency. Biofortification emerged as a possible solution in the global research system (Van Ginkel & Cherfas, 2023). In recent years, in particular since 2010, GMO breeding programmes have entered a second phase with new objectives with biofortication at the heart. The implementation of biofortification was supposed to offer several advantages: the increased production of basic crops, a positive sustainable impact on the environment, with the promotion of environmentally resistant breeding products, cheap breeding maintenance after the initial investment, and increased accessibility to rural and restricted areas (Dhaliwal et al., 2022). But assessment of the new biofortified GMO varieties must be improved to compare their nutritional contents with those of other modern crop varieties (high-yield varieties), especially tubercules, since data on cereals are already available (Ofori et al., 2022). There are several examples of biofortification combining high yields with high micronutrient levels (Ashokkumar et al., 2020; Duo et al., 2021; Velu et al., 2019). However, higher micronutrient content in genetically biofortified crops may be at the expense of yield (Raatz, 2018; Van Ginkel & Cherfas, 2023). Concentrations of minerals in grains depend on complex traits, controlled by multiple functional pathways, including absorption from the soil by roots, translocation from root to shoot and allocation to developing grain (Mori, 1999). Breeding for both high yield and micronutrient concentrations is challenging (Joukhadar et al., 2021). Breeding efforts are further complicated by the environment, soil type, and soil fertility, which all influence micronutrient accumulation (Lowe et al., 2020). As a result, biofortified varieties may require more nitrogen and more micronutrients in the environment (Zn or Fe) to express their potential. The introduction of high-yielding biofortified varieties in cropping systems has thus often required the intensification of these systems including increased use of chemical inputs and fossil energy, thereby increasing both farmers' dependency on the chemical industry and risks for the environment. Therefore, where agricultural soils are depleted (Stewart et al., 2020), biofortified crop varieties rely on the use of costly inputs. In the absence of government subsidies, smallholders revert to local landraces with lower market value (Snapp et al., 2018; Vidigal et al., 2020).

After the high cost of seed innovation (mainly covered by international programmes such as HarvestPlus, a CGIAR Challenge Programme http:/www.harvestplus.org), the recurring costs of dissemination are assumed to be lower than those in other strategies (Bouis et al., 2011). However, while transgenic approaches account for more than 60% of the research on biofortification in terms of the number of cultivars released, the success rate remains low (Garg et al., 2018). National regulations limit the dissemination of the few varieties that are available. Once in place, the production and consumption of biofortified varieties largely depends on government and international funding. In practice, the cost-effectiveness of biofortification is often restricted to large-scale crop production and commercial seed supply systems. Further, the applicability of biofortification remains uncertain given the diversity of food cultures, weak seed systems, scarce and irregular processing, and cooking resources (Johns & Eyzaguirre, 2007).

Seed dependency should also be recognised as a major obstacle to the success of any biofortification strategy. This is particularly true of family farming of the Global South. Even if farmers receive the first seeds cost-free when biofortification programmes are launched, nothing is usually done to set up a long-term programme. In fact, farmers are forbidden to produce seeds for the following crop cycle because seeds are patented. Thus farmers' dependency on seed companies to be able to follow biofortification strategies is perpetuated (Cummings et al., 2023). What is more, farmers often have inadequate access to reliable information when choosing transgenic crops, some of which may be associated with toxic, allergenic, and genetic hazards, hence jeopardizing the very purpose of farming (Vega Rodríguez et al., 2022; Zakaria et al., 2022). Indeed, adoption of these new GMOs biofortified varieties could put the nutritional security of the whole food system at risk by introducing new types of toxicity. The ethical principles of the right to informed choice should be respected, and many countries actually have taken precautionary measures for transgenic crops to avoid possible damage to the environment and health (Muzhinji & Ntuli, 2021).

Because of his focus on few cultivated varieties, biofortification might have adverse effects such as over-dependence on high calorie, starchy staples, which will ultimately erode agrobiodiversity in cropping systems (Bélanger & Pilling, 2019). The gradual replacement of locally adapted landraces or cultivars by few staple crops over-simplifies cropping and farming systems, making them vulnerable to global changes. The adaptive capacity of small-holders is jeopardised while their dependence on global commodities simultaneously increases (Katz-Rosene et al., 2023). This process may undermine efforts to conserve local neglected and underutilised species. Yet, neglected and underutilised species, including traditional fruits, vegetables and legumes, are often rich in micronutrients, adapted to local climatic and soil conditions, locally available and contribute significantly to nutrition security (Adhikari et al., 2017; Jacob et al., 2023; Massawe et al., 2015).

3.2 Dietary diversification and Agri-food systems

Diversification of agricultural production has been promoted as the most sustainable way to guarantee a more diversified diet for both farmers and the general population (High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, 2019). Yet, even though most studies show a positive link between agricultural and dietary diversity, the relationship is complex and depends to a great extent on the spatial scales and on the contexts. At farm level in LMICs, agrobiodiversity can increase the availability and accessibility of diversified food for poor farmers, particularly where agricultural biodiversity is low (Jones, 2017) e.g. in sub-Saharan Africa (Sibhatu & Qaim, 2018; Waha et al., 2022). Agricultural diversification can also provide farmers with additional income and different livelihood options, thereby increasing their resilience to the risk of seasonal shortage, natural disasters and price volatility (Thrupp, 2000). Farm income from the sale of agricultural products can also contribute to dietary diversity by making it possible to purchase food at markets (Dillon et al., 2015; Sibhatu et al., 2015). This seems especially true in Burkina Faso when the income is managed by women (Lourme-Ruiz et al., 2022). In the other extreme, where specialising in monocrops for export takes place, negative externalities affect the environment, increase farmers' incomes may not occur, and a negative effect on diets may take place. Indeed, specialisation toward monocrops for export has been proven to reduce dietary diversity among cotton growers in Burkina Faso (Lourme-Ruiz et al., 2021, 2022) and to affect the nutritional status of the children of oil palm growers in Guatemala (Milovich & Villar, 2022).

Beyond providing food, agricultural diversification is an important lever to improve the sustainability of food systems at different scales. At the farm and regional scales, increasing agrobiodiversity may benefit farmers by improving agricultural productivity and providing ecosystem services (Beillouin et al., 2021; Malézieux et al., 2022). Crop diversity has also been identified as an effective way to cope with climate change-induced crop yield decrease and nutritional quality decline (Food and Agriculture Organization of United Nations, 2015). Agricultural diversification is furthermore often more labour-intensive, and so may increase rural employment opportunities especially for young people in LMICs, especially in sub-Saharan Africa, where rapid population growth and intense pressure on land occur (Giordano et al., 2019).

Promoting dietary diversity worldwide would encourage diversification of plant species worldwide. International trade contributes shaping food systems, either positively by enabling access to a wider range of foods in many countries, or negatively through the standardisation of diets and by reducing the number of species cultivated around the world (Khoury et al., 2014). At a global scale, the demand for, and the production of more diverse and nutrient-dense foods could reduce input-intensive monocropping in favor of the cultivation of vegetables, fruits, and legumes, as well as encouraging the conservation of traditional and indigenous plants (Fanzo et al., 2013). Recent studies point to certain levers, including reducing the consumption of red meat or sugar while increasing the consumption of fruit, vegetables, nuts, and legumes to ensure healthier diets and limit the environmental impacts of food systems (Beal et al., 2023; Coleman et al., 2021; Laine et al., 2021; Stylianou et al., 2021; Tilman & Clark, 2014; Willett et al., 2019).

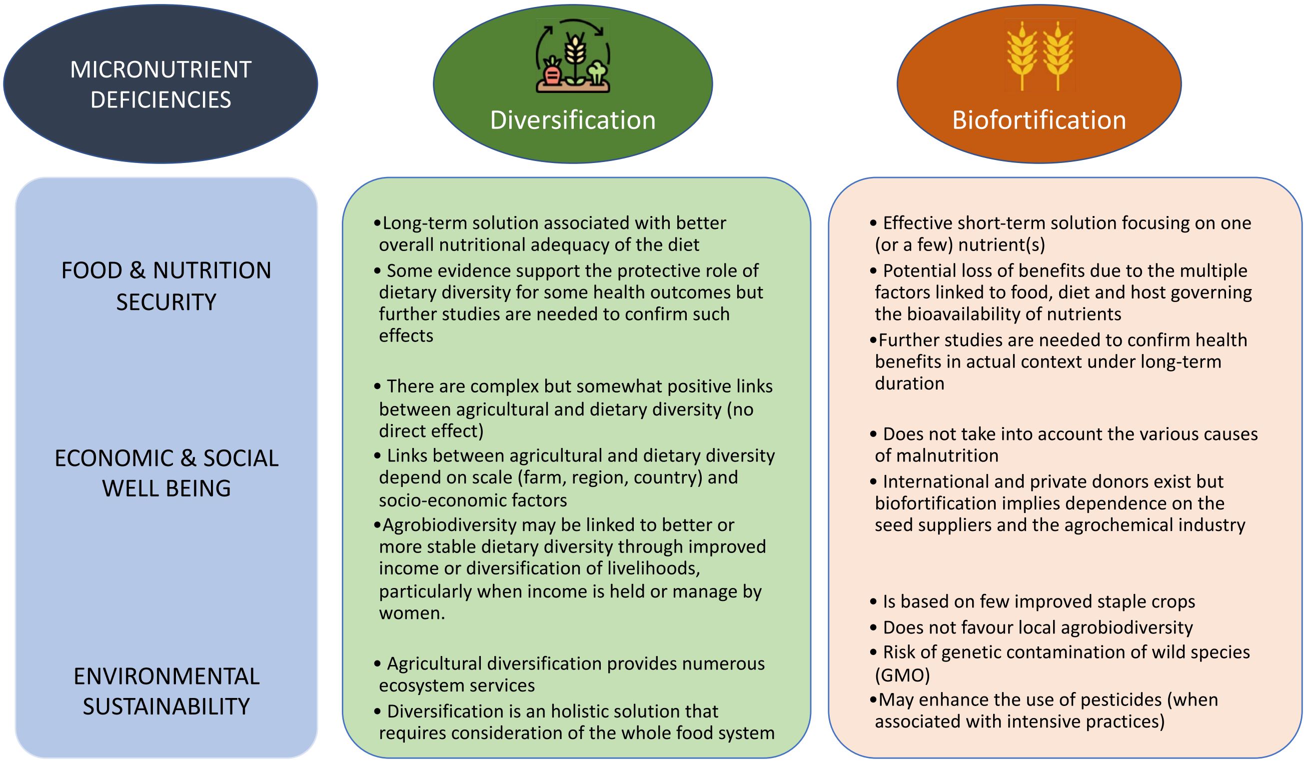
4 Biofortification and diversification from a political perspective

Diversification has long been under-promoted in the LMICs compared to biofortification and supplementation, which appear to be the preferred solutions in nutritional policies supported by the health sector (Delisle, 2003; Kimura, 2013; Van Ginkel & Cherfas, 2023). This observation is still valid today, although improving dietary diversity is now higher on political agendas as a result of the emergence of a multisectoral approach to nutrition and an interest in nutrition-sensitive agricultural interventions (Food and Agriculture Organization of United Nations, 2013; Food and Agriculture Organization of United Nations, 2017). It is worth noting that in many industrialised countries, diversified diets are strongly promoted by public authorities, sometimes through dietary guidelines, as is the case in the UK, France (Hercberg et al., 2008), Australia (National Health and Medical Research Council, 2013) and several Scandinavian countries.

Biofortification and diversification involve different types of economic actors and are supported by asymmetric economic interests. Biofortification was developed through the HarvestPlus program, and was supported by a large international agricultural research consortium (CGIAR), with significant funding from large public and private donors including the World Bank, USAID, DANIDA, the ADB, and the Bill and Melinda Gates Foundation (Kimura, 2013). The HarvestPlus programme proposes a technology which also matches the interests of international seed and fertiliser companies and is apparently well received by policy makers, probably because it is a technology-driven approach that is perceived as a “magic bullet”, echoing the micronutrient movement of the 1990s with supplementation and food fortification (Horton and Wesley, 2008). Biofortification is also an explicit target for breeders as well as for governments and donors, which usually structure and orient their support for agriculture around a few priority value chains, mostly staples (Pingali, 2015). Apparent simplicity helps making biofortification very attractive to both policy makers and donors (Ginkel and Cherfas, 2023).

By contrast, dietary diversification involves a food system approach with multiple food chains, which are usually run by small-scale economic operators in the LMICs. Donors and states support a number of projects that aim to improve dietary diversity, however these projects are scattered across national territories and are implemented at relatively small scales. Unlike biofortification, dietary diversification projects do not involve large coalitions of powerful actors. In other words, a diversification strategy is not currently being promoted by any major international research programme supported by large-scale public and private donors and, perhaps most importantly, is not linked to any powerful economic interests. Political economy thus appears to help explain the imbalance in political interests and support for the two pathways.

Overall, actors promoting biofortification have benefited from a favourable political agenda on strengthening agriculture-nutrition linkages. Biofortification has been presented as a nutrition-sensitive agricultural intervention, and one which has been proved to be cost-effective compared to others actions aimed at improving dietary diversity (Ruel et al., 2018; Sharma et al., 2021). The amount of research using randomised controlled clinical trials to demonstrate the impact of biofortification on micronutrient status and its cost-effectiveness is then viewed as an advantage compared to research on other nutrition-sensitive agricultural



MICRONUTRIENT DEFICIENCIES	Diversification	Biofortification
FOOD & NUTRITION SECURITY	• Long-term solution associated with better overall nutritional adequacy of the diet • Some evidence support the protective role of dietary diversity for some health outcomes but further studies are needed to confirm such effects	• Effective short-term solution focusing on one (or a few) nutrient(s) • Potential loss of benefits due to the multiple factors linked to food, diet and host governing the bioavailability of nutrients • Further studies are needed to confirm health benefits in actual context under long-term duration
ECONOMIC & SOCIAL WELL BEING	• There are complex but somewhat positive links between agricultural and dietary diversity (no direct effect) • Links between agricultural and dietary diversity depend on scale (farm, region, country) and socio-economic factors • Agrobiodiversity may be linked to better or more stable dietary diversity through improved income or diversification of livelihoods, particularly when income is held or manage by women.	• Does not take into account the various causes of malnutrition • International and private donors exist but biofortification implies dependence on the seed suppliers and the agrochemical industry
ENVIRONMENTAL SUSTAINABILITY	• Agricultural diversification provides numerous ecosystem services • Diversification is an holistic solution that requires consideration of the whole food system	• Is based on few improved staple crops • Does not favour local agrobiodiversity • Risk of genetic contamination of wild species (GMO) • May enhance the use of pesticides (when associated with intensive practices)

Fig. 2 Potentials and limits of biofortification and diversification considering food and nutrition security, economic and social well-being, and environmental sustainability

interventions based on statistical correlation studies (Avallone et al., 2021; Ruel et al., 2018).

Each of the proposed pathways also has important consequences in terms of independence and national food sovereignty. Kimura (2013) and Scrinis (2016) show that biofortification is a solution over which countries suffering from food insecurity, and *a fortiori* their populations, have no control. Implementing biofortification would therefore make these countries dependent on technological systems and oligopolies. This criticism is similar to that of industrial agriculture, particularly by the early advocates of agroecology (e.g., Gliessman, 2016), who deplored farmers' dependence on seed companies, fertilisers, pesticides and, increasingly, on electronics and big data. The re-emergence of the question of food sovereignty following the Covid 19 crisis and the war in Ukraine has revived this criticism.

5 Conclusion

Figure 2 summarises the potential and limits of biofortification and of dietary diversification from the points of views of: (1) human health, (2) economic and social well-being, and (3) agricultural and environmental sustainability. Although biofortification may be an effective way to tackle specific micronutrient deficiencies, the strategy should be seen as a short-term technical fix, whose potential may be reduced by complex bioavailability mechanisms and dietary behaviour. By contrast, diversification should be seen as a long-term strategy leading to improved overall nutritional adequacy.

Addressing the challenge of micronutrient deficiencies, but also of malnutrition in all its forms, requires a shift from a linear approach to a holistic, multidisciplinary, and multisector approach. Widespread use of biofortified foods as a way to tackle malnutrition not only oversimplifies the challenge posed by malnutrition, but could have serious consequences on the whole food system, with adverse impacts on the environment, in addition to social and economic impacts. Proposing a single-factor solution to an issue with multiple social, economic, and cultural roots fails to recognize the need for a profound transformation of food systems.

Diversification appears to be a solution that countries, farmers, and consumers can control. Unlike a stand-alone solution, diversification may be adapted to any different particular context, reflecting each specific agronomic and climatic characteristics, but also associating the local food cultures. Dietary diversification could thus enhance the sustainability of food systems at different scales. However, the implementation of diversification requires long-term structural and ambitious changes, such as the transformation of production systems, the organisation of efficient value chains for healthy but perishable foods, public regulations favouring nutrient-rich foods, and improved consumer information. Successfully addressing these challenges requires a coordinated approach between public health, agriculture and consumers.

Regardless of the type of nutritional intervention strategy used, accounting for the broader food and consumption context is a prerequisite for sustainable nutrition and health. The key to good nutrition must remain a healthy, balanced diet, which in turn implies access to a variety of foods and the implementation of the right to food (Food and Agriculture Organization of United Nations, 2005). Malnutrition in LMICs is part of a global nexus where it combines with poverty and disease, within a strong frame of social and economic facts and constraints (Adeyeye et al., 2023; Owolade et al., 2022). Taking the agricultural, health, educational, and social aspects into consideration and addressing poverty reduction are part and parcel of any successful strategy.

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Declarations

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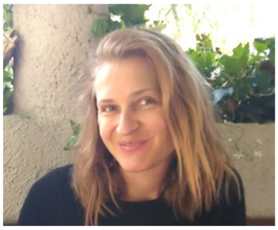

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