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Feature Review

Diversifying Food Systems in the Pursuit of Sustainable Food Production and Healthy Diets

Sangam L. Dwivedi,[1] Edith T. Lammerts van Bueren,[2,3] Salvatore Ceccarelli,[4] Stefania Grando,[1] Hari D. Upadhyaya,[1] and Rodomiro Ortiz[5,*]

Increasing demand for nutritious, safe, and healthy food because of a growing population, and the pledge to maintain biodiversity and other resources, pose a major challenge to agriculture that is already threatened by a changing climate. Diverse and healthy diets, largely based on plant-derived food, may reduce diet-related illnesses. Investments in plant sciences will be necessary to design diverse cropping systems balancing productivity, sustainability, and nutritional quality. Cultivar diversity and nutritional quality are crucial. We call for better cooperation between food and medical scientists, food sector industries, breeders, and farmers to develop diversified and nutritious cultivars that reduce soil degradation and dependence on external inputs, such as fertilizers and pesticides, and to increase adaptation to climate change and resistance to emerging pests.

Trends

Intensive industrial agriculture does not appear to be sustainable and does not contribute to a healthy human diet.

Reduced consumption of livestock products and increased use of plant products are central to reducing food carbon footprints and healthy eating.

Fundamental to better health is understanding gene–nutrient interactions in growth and development and in disease prevention; genomics and phenomics may assist selecting for nutritionally enhanced, resource use-efficient, and stress-resilient cultivars.

A paradigm shift is occurring from the current production/productivity goals to developing nutritionally enhanced and resource use-efficient crops.

There is growing notion that not all healthy diets are sustainable and not all sustainable diets are healthy, thus an integral system approach will be necessary to produce sufficient, safe, and nutritionally enhanced food.

The Importance of Seed Biology for Food Security

Current global issues under debate include the decline of **biodiversity** (see Glossary), climate change and **greenhouse gas** emissions (GHGEs), hunger and **malnutrition**, and poverty and water scarcity. Diet related-diseases such as diabetes and those associated with being **overweight and obese** are additional global problems. We review here and lay open how all these issues are related to different aspects of seed production (i.e., yield, quality, genetic features, and trade). The delivery of agricultural innovations such as **bred-seeds** also requires long-term funding for plant sciences (Box 1).

Diet × Gene Interaction and Human Health

The microbiota in the gut play an essential role in human health. The evidence to date suggests that the gut microbiota is involved in malnutrition and obesity, and dietary intervention impacts on gut microbial diversity and human health [1–3].

The increase in the prevalence and progression of **chronic (non-communicable) diseases** associated with the modern human diet, relative to that of hunter-gatherers [4], is the consequence of a complex interplay between genetic and environmental factors, of which diet plays an important role. The average effects of diet are masked by individual genetic predispositions, and genetic variants showing robust associations with differences in dietary patterns are present in diverse ethnic groups. For example, individuals carrying *SIRT6 rs107251CT/TT*

[1]International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502324, India
[2]Louis Bolk Institute, Hoofdstraat 24, 3972 LA Driebergen, The Netherlands
[3]Wageningen University and Research, PO Box 386, 6700 AJ Wageningen, The Netherlands
[4]Rete Semi Rurali, Via di Casignano,

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25 50018 Scandicci (FI), Italy
[5]Swedish University of Agricultural Sciences, Department of Plant Breeding, Sundsvagen, 14 Box 101, 23053 Alnarp, Sweden

*Correspondence:
rodomiro.ortiz@slu.se (R. Ortiz).

Box 1. Agricultural Innovations Require Funding for Plant Sciences

Innovations often arise not from planned research but from unexpected sources. For example, modern biology benefited from the discovery of *Taq* polymerase from photosynthetic organisms found along a thermal gradient in Yellowstone National Park [135], which brought immense benefits to medicine and industrial agriculture. Had D.F. Jones at Bussey Institution in Harvard University, G.H. Shull at Cold Spring Harbor, or E.M. East at Connecticut State College not begun their experiments to understand heterosis, farmers would have continued to grow open-pollinated cultivars [136,137]. This discovery of heterotic effects in crop productivity led to significant agricultural innovations, for example, hybrid maize emerged from being unknown at the beginning of the 20th Century to being grown by most US farmers by the mid-century [137]. These examples highlight how investments in basic research lead to making discoveries of significant importance to society.

Investments in plant sciences at large contribute to enhancing both productivity and sustainability, thus accelerating agricultural growth, building resilience to changing climates or to stress-prone environments, and developing agro-ecosystems with reduced GHGE. Concerns about global food shortages in the 20th century triggered a surge in public and private investment in agricultural research-for-development (AR4D), which led to the emergence of the ‘green revolution’ that has had a significant impact on agriculture, the environment, and livelihoods, worldwide [138]. Thereafter, the United Nations suggested that nations should at least spend 1% of agricultural gross domestic product on AR4D, but this differs widely between regions and countries.

Anxiety over food security resurfaced when food prices increased substantially towards the end of past decade, leading to political unrest in many parts of the world. This situation largely ensued because of a decline in public investments in plant sciences (including AR4D) after the green revolution, which led to a slowdown in productivity growth among the main cereals, such as rice and wheat. By contrast, multinational corporations invested heavily in the seed business, particularly focusing on major crops and F_1 hybrids with major return of investment, such as maize, rapeseed, canola, and cotton, and use patents to protect their intellectual property rights. As a result, the private sector assumed an increasing share of AR4D and ownership of emerging (bio)technologies [139], which could influence changes in the strategic direction of plant sciences. Furthermore, the supply of products and other research outputs as **international public goods** (IPGs) has become increasingly constrained by variable funding. There has recently also been a push towards downstream product adaptation and dissemination in international AR4D, instead of carrying out innovation and product development. The unintended consequences of this declining funding and its switch towards adaptive research could be a break in the research pipeline that provides IPGs that enhance sustainable agricultural productivity growth [140,141]. Policymakers should remember that funding to plant sciences needs to keep pace to permit ongoing innovations to increase food availability, assure its affordability, and enhance its nutritional content and safety, such that the population can maintain a healthy and active life.

alleles with a low intake of soybean in their diet have a significantly decreased risk of arteriosclerosis [5], while those carrying the *rs2383206* allele and depending on a diet high in red and processed meat, but low in fruits and vegetables, have increased risk for myocardial infection [6]. Similarly, individuals with a diet low in antioxidants (vitamins A, C, and E) and carrying *TXN rs2301241* or *COMT rs740603* alleles are more prone to obesity [7], while those having a high-fat diet and carrying the *rs1801282* allele are more likely to suffer from **insulin resistance** and type 2 diabetes [8,9]. Celiac disease is a chronic and immune-mediated intestinal disorder that is caused by intolerance to ingested gluten (**gluten intolerance**). To date, 40 celiac disease-associated loci are known, and many overlap with those of other immune-related diseases [10]. Connections between diet and genetic predispositions are being unraveled through advances in **nutritional genomics** and knowledge of variations in human genomes. These advances contribute to our understanding of the pathogenesis and better management of chronic disease through proper dietary choices [11]. The translation of genome-scale variation into medically useful information, however, remains distant [12].

Holistic Versus Reductionist Approach to Food and Human Health

There is increasing evidence that refined food increases risks of chronic diseases [13]. Some authors argue that applying reductionist approaches in food science (associating single food compounds to single physiological effects) has led to fractionated, highly processed and refined food [14]. This has brought **preventive nutrition** into a pharmacological focus, producing drugs (supplements) containing nutrients that can be isolated and added to products at high doses. However, there is now a need to take a holistic approach to capture the complexity of nutrition in relation to health to ensure that the reductionist research can be beneficial [15]. The recognition that nutrition–health interactions are complex indicates that they cannot be modeled on the basis of a linear cause–effect relation between one food compound and one physiological effect, but must instead be based on multicausal nonlinear relations. In this context, it is also important to focus on eating habits and not only on single food components.

New transdisciplinary research strategies will be necessary to understand the complex relationship between diet and health, and to learn more about **optimal nutrition** [16]. For a more effective research and policy on nutrition, the whole concept of food synergy puts 'thinking food first'. This concept supports the idea of dietary variety and of selecting nutrient-rich foods rather than building up from isolated constituents or supplements [14,17].

Carbon Footprints in Relation to the Energy and Nutrient Density of Foods

Rising incomes and urbanization are driving a global dietary transition, and diets increasingly have higher proportions of refined sugars, refined fats, oils, and meats [18]. By 2050 these dietary trends, if unchanged, would be a major contributor to an estimated 80% increase in GHGEs from food production and land clearing. Keeping these numbers in mind, dietary changes worldwide can have multiple health, environmental, and economic benefits [18–20]. It is well established that animal-based products have a higher environmental impact than plant-based products [21–24]. For example, age-and-sex-adjusted mean GHGEs were 7.19 for high meat-eaters, 5.63 for medium meat-eaters, 4.67 for low meat-eaters, 3.91 for fish-eaters, 3.81 for vegetarians, and 2.89 for vegans [23]. Thus, reducing the fraction of animal-source foods in human diets can lead to benefits for both the environment and human health. Transitioning towards more plant-based diets could reduce global mortality by 6–10% and food-based GHGEs by 29–70% [25] compared to a reference scenario provided by the Food and Agriculture Organization of the United Nations in 2050 [26,27]. However, significant changes in the global food system would be necessary for regional diets to match the dietary changes discussed above [25].

A healthy and sustainable diet is defined as one that provides all essential nutrients including minerals and vitamins, but with low environmental impact. How much can dietary GHGEs be reduced without impairing nutritional adequacy, affordability, and acceptability? A modeling study to guide sustainable food choices revealed that moderate GHGE reductions ($\leq$30%) are compatible with nutritional adequacy and affordability without adding major food-group shifts to those induced by nutritional recommendations. Higher GHGE reductions either impaired nutritional quality – even when micronutrient recommendations were imposed – or required non-trivial dietary shifts that compromise acceptability to reach nutritional adequacy [28].

Governments should consider policy options that include taxation of unhealthy diets and supporting healthy diets to discourage eating unhealthy cheap diets. Incorporating societal costs of GHGEs into food prices has therefore potential to improve health, reduce GHGEs, and raise revenue [29–31].

Adopting Cropping Systems That Enhance Nutritional Diversity

Hunger and malnutrition continue to be staggering challenges, and $\sim$800 million people are still undernourished and about half of the world population lacks one or more essential nutrients [18,32,33]. Most food originates directly or indirectly (via animal feed) from crop plants, and food affects human health [34–37]. Crop total diversity has narrowed over the past 50 years, and consequently composition of the diet at the global level has become more uniform at the expense of regionally important crops, as shown by a mega-study across 150 countries. This lack of dietary diversity is an additional threat to **food security** and human health [38]. This

Glossary

Biodiversity: diversity among and within plant and animal species in an environment.

Bred-seeds: genetically improved seeds developed by crossbreeding or biotechnology methods such as marker-aided selection or genetic engineering.

Chronic (non-communicable) disease: a persistent disease that is long-lasting in its effects or develops over time.

Conservation agriculture: an approach for managing agro-ecosystems for improved and sustained productivity, increased profits, and food security while preserving and enhancing the resource base and the environment.

Evolutionary breeding: natural selection acting upon a heterogeneous mixture of genotypes over generations and across environments such that traits positively correlated to reproductive capacity increase over time.

Food security: when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food.

Gluten intolerance: allergic reaction in humans caused by eating food containing gluten protein that is mostly present in wheat, rye, and barley.

Greenhouse gas: carbon dioxide, methane, nitrous oxide, and ozone in an atmosphere that absorbs and emits radiation within the thermal infrared range.

Green revolution: an agricultural development strategy based on the combined use of new cultivar, fertilizers, irrigation water, and mechanization.

Insulin resistance: a condition in which the body produces insulin but does not use it effectively, thus building up glucose in the blood instead of being absorbed by the cells, which leads to type 2 diabetes.

International public goods (IPGs): a non-rivalrous and non-excludable good available worldwide.

Malnutrition: a condition that results from eating a diet whose nutrients are either insufficient or are in excess such that the diet causes health problems.

Nutrient use efficiency (NUE): the amount of biomass produced per unit of nutrient supplied.

finding stresses the importance of diversifying farm production and facilitating access to market to improve dietary diversity on subsistence farms [39,40]. India practices more than 20 cropping systems, with rice (*Oryza sativa*)–wheat (*Triticum aestivum*) and rice–rice being the most important. The rice–wheat cropping system (RWCS) of the Indo-Gangetic Plains region of South Asia revolutionized agriculture during the **green revolution** which, on the one hand, enhanced food and **nutritional security**, and displaced legumes from the system on the other. The RWCS has shown declines in system productivity *per se*. A great resurgence of malnutrition has been observed among South Asian populations depending entirely on rice and wheat, with micronutrient deficiency being the major cause of malnutrition. Diversification of the RWCS with legumes and vegetables will increase dietary diversity and enrich soil health, thereby leading to enhanced system productivity and sustainability of this agro-ecosystem [41].

The problem of the lack of crop diversity leading to a loss of dietary diversity is not only a problem of the developing world but also of the industrialized world. Wallinga [42] demonstrated the relationship between US cheap food policy, including subsidies for few commodity crops, and the replacement of hunger by obesity, and pleads for a more diverse farm policy to stimulate the production of vegetables and fruits.

The nutritional functional diversity (NFD) of the cropping system, which is based on both on-farm plant species composition and nutritional composition, has the potential to address malnutrition. NFD value increases when a crop with a unique nutrient combination is added to the community, and decreases when such a crop is lost. Assessing the nutritional diversity of cropping systems guides management decisions towards increased nutrient diversity for a given number of species, as well as towards increased redundancy or buffers of species for specific nutrient sets. Such an approach has radically changed nutritional diversity outcomes, as noted after adding or removing individual species in 133 villages in Malawi [43]. Farm production diversity was consistently and positively associated with dietary diversity, and this association was significantly greater in women-headed households than in those led by men. Legume, vegetable, and fruit consumption was strongly associated with greater farm diversity, with more diverse production systems contributing to more diverse household diets [44,45]. A strong positive association was noted between production and dietary diversity among younger children (6–23 months), and there were significant positive associations between production diversity and height for age *Z*-scores and stunting among older children (24–59 months) [46]. This research highlights the relationship between production and dietary diversity, which leads to improved human health and wellbeing. However, such a relationship is complex and is influenced by gender, wealth, household decisions, market access to agricultural production, and the specific nature of on-farm crop diversity [44]. In addition, the age, education level, and employment status of the individuals concerned, as well as social tradition, also influence the choice of dietary intake and human health [47].

Has Pursuit of Increased Yield Compromised Biodiversity and Nutritional Quality?

With the transition to modern **plant breeding**, selection for specific adaptation was replaced by selection for wide adaptation – the basic breeding principle adopted by the green revolution – which reduced the looming danger of famines but left a legacy such as leaching into ground water of fertilizer residues because of their overuse [48], water shortage, the emergence of pesticide resistance [49], an increase in the population of harmful insects [50], and bypassing of farmers in marginal areas [51]. Such adverse effects were also noted by the contamination of soil, water, and air with persistent pesticides, and soil degradation such as reduction of organic matter, salinity, and acidification [52]. Diversity was replaced by uniformity as a result of a plant breeding approach that was not the most efficient with respect to robustness [53]. Maximizing

Nutritional genomics: the study of the relationship between the human genome, nutrition, and health.
Nutritional security: access to nutritional foods by all people at all times, with adequate absorption and utilization of food nutrients, allowing individuals to live a healthy and active life.
Optimal nutrition: eating the right amounts of nutrients on a proper schedule to achieve the best performance and the longest possible lifetime in good health.
Overweight and obesity: body mass index (BMI), a measure of overweight and obesity, is obtained by dividing body weight in kg by height in m^2. BMI $\geq$25 and $\geq$30 refer to overweight and obesity, respectively.
Participatory plant breeding: a breeding method in which farmers are involved in the selection of breeding populations leading to the development of locally adapted cultivars based on farmer-preferred traits.
Plant breeding: the science responsible for the type and diversity of seed that farmers plant, and hence for the diversity of food that we eat.
Preventive nutrition: dietary interventions aiming to prevent or delay the onset, or reduce the seriousness, of disease and disease-related complications.
Quantitative trait loci (QTLs): DNA segments carrying genes controlling quantitative traits.

crop yield while at the same time minimizing crop failure for sustainable agriculture therefore requires a better understanding of the impacts of plant breeding on crop genetic diversity [54].

Modern food systems are often not driven by taste and nutritive value but by factors such as consistency, predictability, low cost, and high yield [55]. Modern breeding programs have primarily focused on edible yield, host plant resistance, and low labor input (e.g., driving herbicide-resistant cultivars) rather than on nutritional and functional characteristics. Hence, little attention has been given to the selection of cultivars according to nutritional value [56,57]. Research to improve the nutritional quality of plants has historically been limited by a lack of basic knowledge of plant metabolism and the compounding challenge of resolving the complex interactions of thousands of metabolic pathways [58], as well as by adverse environmental effects, as indicated earlier (see also http://ec.europa.eu/science-environment-policy).

The general perception – that progress towards increasing quantity has led to a price being paid in terms of quality – has not actually been thoroughly investigated due to high analytical costs and large environmental influence on plant nutritional values. However, in 1997, a marked reduction of several minerals in 20 fruits and 20 vegetables was found in the UK in comparison to food composition data from the 1930s and 1980s [59]. In 1998, a US Department of Agriculture comparison of food composition data between 1975 and 1997 suggested an 'alarming decline in food quality' in 12 common vegetables [60]. This trend has been confirmed and updated with more recent research between 1940 and 2002 [61].

The notion that quantity and quality cannot progress together is not true in several crops for micronutrients such as iron, zinc, and vitamin A. Breeding for high trace-mineral density in seeds will not always incur an edible yield penalty. On the contrary, such a micronutrient enhancement may have important spin-off effects for an environmentally friendly increase in farm productivity in the developing world [62].

The paradigm of agricultural development based on maximizing grain yield in major cereal crops [63] led to increased production of high-yielding bread wheat, rice, and maize (*Zea mays*) and replacement of other more nutrient-rich cereals [64]. Between 1961 and 2013, the land area planted with wheat, rice, and maize increased from 66% to 79% of all cereals [65], while the land area planted with other cereals such as barley (*Hordeum vulgare*), millet, oats (*Avena sativa*), rye (*Secale cereale*), and sorghum (*Sorghum bicolor*) – which have higher nutrient content – declined from 33% to 19%. As a result, the energy density of the cereal supply remained constant between 1961 and 2011, but the protein, iron, and zinc contents in the global cereal supply declined by 4%, 19%, and 5% respectively, with an overall decline of the nutrient-to-calories ratio [64].

Nutritional quality has been compromised by the emphasis on edible yield and through the loss of biodiversity [66] caused by the introduction of high-yielding uniform cultivars and breeds: today 95% of the world's calories come from 30 species, but almost half of the global calorie demand is supplied, as noted above, by three crops, namely maize, rice, and wheat. Of 30 000 edible species, only about 150 are grown. This loss of diversity alone has had significant negative health consequences [67]. It is therefore urgent to promote agro-biodiversity on farms or through local production to meet the growing demand for safe and nutritious food.

Developing Resource Use-Efficient and Nutritionally Enhanced Crops

Stresses – exacerbated by climate change – are serious threats to crop production worldwide at a time when the staple food supply needs to be significantly increased to meet the demands of the growing human population. Africa, Mesoamerica, and the Andes, plus South and Central Asia, will be severely affected by global warming. Many inhabitants of these regions have a very limited capacity to adopt mitigation strategies. Crop yield and quality is linked to climate change because farmers will need cultivars that can cope with the future climate. Plant breeding for adaptation to climate change must address a moving target that differs across geographical locations [68,69]. Developing climate-resilient crops as well as integrated natural resources management may minimize the adverse impact of climate change on agriculture.

Evolutionary Breeding

Crossbreeding has often been ineffective in addressing many of the needs of low-input farming systems, particularly in stress-prone sites [70]. **Evolutionary breeding** [71,72] uses modern science to bring back diversity in farmers' fields and thereby enhance crop resilience. It consists of planting mixtures of many different genotypes of the same crop, preferably but not necessarily using early-segregating generations. These evolutionary populations (EPs) are planted and harvested year after year and, because of natural crossing (higher in cross-pollinated and less in self-pollinated crops), the genetic composition of the seed that is harvested is never the same as that of the planted seed. An EP evolves therefore to become progressively better adapted to the environment where it grows. Because climatic conditions vary from one year to the next, the genetic makeup of the population fluctuates, and the genotypes better adapted to stressful environments gradually become more frequent [73]. EPs of barley, bread and durum (*Triticum durum*) wheat, common bean (*Phaseolus vulgaris*), maize, rice, summer squash (*Cucurbita pepo*), and tomato (*Solanum lycopersicum*) are currently grown [74]. Farmers using EPs report high yields and low levels of weed infestation, disease incidence, and insect damage. The use of pesticides has consequently been reduced. Iranian and Italian farmers growing wheat EPs reported that bread derived from the flour of these EPs can also be consumed by customers suffering from gluten intolerance [75]. Farmers in France and Italy found that EPs bring not only great yield stability but also enhanced bread aroma and quality [75]. Iranian nomads also found an improvement in the quality of sheep milk after using a barley EP as feed. Therefore, evolutionary and evolutionary–**participatory plant breeding** adapts crops to various stresses, to different types of agriculture, and to climate change. It is also an appropriate method to produce suitable and diverse cultivars that help farmers to reduce dependence on external inputs, as well as vulnerability to climate change and to the associated emerging pests and diseases. As within-crop and cultivar diversity increases [34], so does the diversity in human diet, thus contributing to both food security and to a healthier diet. The major drawback of EPs has been the perception that EP can only produce populations which, until recently, could not comply with the standards required for variety registration that have moved over time towards more uniform pure lines and F_1 hybrid cultivars. Although this perception is incorrect [76], it has discouraged using EPs even in the developing world where the same standards are being applied, even though the formal seed system supplies a very small proportion of what farmers sow, often well below 10% [77]. This is likely to become less of a problem because the European Commission is now implementing directive 2014/150/EU [78], which makes possible to market experimentally heterogeneous materials of different cereals up to 31st December 2018.

Genomic-Assisted Breeding

Genomics has advanced considerably in the past one to two decades, and reference genomes of many crops are now available. There has been rapid development in high-throughput phenomics and genotyping facilities, with next-generation sequencing technology providing the necessary throughput to discover and introgress allelic variations of target breeding traits [79,80]. These advances now allow multiple traits to be aggregated into an improved genetic background, thus leading to the development of stress-resilient crops. Some of the ensuing cultivars occupy today large acreages, for example submergence- and salinity-tolerant rice in Asia ([81], http://irri.org/our-work/research/better-rice-varieties/climate-change-ready-rice), and yield-enhancing **quantitative trait loci** (QTLs) associated with performance under drought stress have been incorporated into submergence-tolerant versions of three high-yielding Indian rice cultivars. Likewise, *Sub1* has been transferred into highly popular locally adapted rice cultivars to address complete submergence due to flash floods in the major river basins [82]. Furthermore, introgressed lines containing *Saltol* for salt tolerance at the reproductive stage showed high yield potential under stress and non-stress conditions in West Africa [83]. These lines are being evaluated for release as cultivars which would enhance rice productivity. Likewise, *Sub1* and *Saltol* were introgressed into highly popular locally adapted Indian rice cultivars [82]. A major QTL for low-phosphorus (P) tolerance, *Pup1*, is being introduced into locally adapted rice cultivars in Africa and Asia because it is expected to considerably enhance productivity under low-P conditions [84,85].

Introgressed lines containing *Ncl*, which regulates the transport and accumulation of Na^+, K^+, and Cl^-, increased yields by 3.6- to 5.5-fold under salinity, thus facilitating soybean farming in saline-prone areas [86]. Elite bean lines growing 4°C above the limit normally tolerated by this crop became available after introgressing tepary bean genes [87]. A major effort is underway to introgress drought-tolerant QTL into a range of popular chickpea (*Cicer arietinum*) cultivars in Africa and Asia. Chickpea introgression lines in the genetic background of leading Indian cultivars containing a genomic region harboring drought-tolerance QTL showed at least 10% higher yield than recurrent parents. Some of them have already advanced to national trials in India [88].

Breeding for Resource Use Efficiency and Stress-Prone Sites

Crop cultivars with high **nutrient use efficiency** (NUE) will help to sustain production in low-input agriculture by increasing the efficiency of uptake and utilization of nutrients by breeding for suitable root systems. NUE for seed crops is dependent upon the efficiencies of nutrient acquisition (or nutrient uptake) and nutrient utilization. The evidence to date suggests that natural variation for NUE is present in modern germplasm pools and that its exploitation in breeding programs has potential in developing nutrient-efficient crop cultivars [89,90]. For example, *Pup1* allele increases P uptake and confers a significant grain-yield advantage in rice in P-deficient soils [91]. Introgressed lines containing *Pup1* allele significantly increased grain yield on P-deficient soils [92]. Overexpression of a *Pup1-specific protein kinase* gene (*PSTOL1*) significantly enhances grain yield in P-deficient soils. *POSTL1* promotes early root growth, thereby enabling plants to acquire more P and other nutrients [84].

Breeding stress-resilient maize adapted to sub-Saharan Africa led to disseminating 160 drought-tolerant maize cultivars to farmers [93–95]. *Ex ante* assessment of drought-tolerant maize adoption in southern and eastern Africa predicted large positive impacts of increasing average grain yield and improved yield stability [96], while *post ante* assessment of drought-tolerant maize hybrids of early to medium maturity duration showed a yield advantage of 4–19% over commercial control crops, with greater gains under stress conditions [97]. Thus, a huge potential exists for drought-tolerant maize seed production and marketing in Africa. The barriers to adoption include, however, unavailability of improved seed, inadequate information, lack of resources, high seed price, and perceived attributes of different cultivars [98]. Adequate supply of drought-tolerant maize seed in local markets and selling in affordable micropacks (1 or 2 kg) will accelerate adoption in eastern and southern Africa [95].

Breeding Nutritious Crops

Micronutrient enhancement is a sustainable and cost-effective strategy to address malnutrition, and has been included as a core breeding activity to ensure that newly developed cultivars meet human nutritional requirements. Pro-vitamin A-rich maize and seed mineral (Fe and Zn)-dense beans, cowpea (*Vigna unguiculata*), lentil (*Lens culinaris*), pearl millet (*Pennisetum glaucum*), rice, and wheat cultivars were released in some countries in Africa, Asia, and South America

[99]. High concentration of phytic acid in foods limits micronutrients bioavailability [100]. Genotypic differences in bioavailable Fe and Zn were, however, reported in germplasm pools, and this warrants further exploration [62]. Total iron absorption by young women from iron-enhanced pearl millet composite meals is doubled versus regular millet meals [101], suggesting that breeding for micronutrient enhancement is a viable approach in this crop. Likewise, *Gpc-B*, which is a major gene for high grain protein, has been introgressed into several leading wheat cultivars in India [102–104]. 'Ashlock HP5A' is a soybean (*Glycine max*) cultivar with high seed protein and yield that was released in southeast Arkansas, USA (www.agweb.com/article/new-conventional-soybean-offers-high-protein-competitive-yield-naa-chris-bennett).

Quality protein maize (QPM) cultivars were released in Latin America, Africa, and Asia in the past 20 years [105–107]. The evidence to date suggests that substituting QPM for common maize results in improved animal and human health [108–110]. For example, consumption of QPM led to a 12% increase in the rate of growth in weight and a 9% increase in the rate of growth in height in infants and young children with mild to moderate undernutrition from populations in which maize is the major staple food [108], and improves feed efficiency leading to less N in feces [109]. Phenylpropanoids such as flavonoids, anthocyanins, and phenolics have shown beneficial effects on human health [111]. Barley, maize, rice, sorghum, soybean, and wheat cultivars rich in phenylpropanoids are grown in Europe and on the American continent [112].

Analysis of the pattern of adoption of QPM maize revealed that agronomic performance, postharvest processing, taste and flavor, nutritional benefits, and availability of seeds significantly impacted on the adoption of QPM cultivars. High acceptance of β-carotene-rich maize and seed mineral (Fe, Zn)-dense beans, pearl millet, rice, and wheat has also been noticed in some parts of Africa, Asia, and South America. Public awareness and lack of seed availability, among others, have been highlighted as the main factors limiting the adoption process. Thus, developing awareness and strengthening seed production and distribution for better diffusion of nutritionally enhanced crop cultivars should be pursued [62].

Trade-Off

Modern plant breeding has revolutionized agriculture, resulting in several-fold increases in the production and productivity of staple crops. The evidence to date suggests inverse associations between seed yield and resistance to stress (including pathogen, herbivore, and herbicide stress), between seed yield and nutrition, and between soil root biomass and nutrient utilization, which may be due to either genetic linkage or pleiotropic effects. Genetic dilution effects (trade-offs) may be common when selective breeding successfully increases crop yields, while environmental (surface and ground water pollution by nitrates or P losses) trade-offs between seed yield and nutritional quality could result either from the variation in soil health and quality or be due to drought and heat stress during seed development. The challenge for the agricultural research community is to minimize any possible negative trade-offs to provide nutritious staple foods for growing populations [62,113,114].

Systems Approach to Environmental Sustainability and Human Health

Although agriculture, nutrition, and health are closely related, they are often dealt with in isolation and an integrated approach will be necessary to avoid undesired trade-offs such as occurred with the inappropriate use of antibiotics in livestock farming and the threats to human health due to antibiotic-resistant bacteria in hospitals [115,116]. The drivers of sustainable food and nutrition security worldwide, including smallholders, are complex, multilevel, multisectoral, and heterogeneous. To take into account the underlying systems with their structural components, feedback loops, and linkages between agri-food, health, disease, and environmental systems, is challenging and needs further development of transdisciplinary modeling tools for effective designs by both policymakers and scientists [117–119]. The problems faced are different for countries with a large percentage of subsistence smallholders coping with poverty, soil erosion, and low quantity and diversity of crops on their land and in their diet, and for industrialized countries with large-scale intensive farming systems with compacted soils, food surplus, and a high percentage of ultra-processed food in supermarkets. In both situations the goal is to improve soil fertility and to move towards affordable, sustainable, and diverse foods, including a higher percentage of fresh vegetables in the crop rotation, market, and diets. An example of interdisciplinary approach integrating human health and environmental health ('eco-nutrition') was given in the Millennium Villages project in Africa by focusing on the relationship between agro-biodiversity and multiple components of human nutrition as an important and often overlooked ecosystem service [120]. One of their key elements in this project is including nitrogen (N)-fixing plants or trees in the farm system as an important source of free N for soil fertility (up to 200 kg ha^{-1}) and protein for human consumption and health because it replaces animal sources of proteins. An important component of the applied multisector approach is (bottom-up) community empowerment and leadership building on existing and new community committees tackling issues related to health and nutrition, agriculture, education, water, energy, and economic planning, and also interacting with governments on local and national level for top-down support [120].

There are several examples of research in South Asia to incorporate more vegetables in crop rotations to improve food security, quality of diet, sustainability, trade development, and income generation [121,122]. For example, several scenarios were analyzed to improve the current narrow rice and wheat systems by various combinations of best agronomic management practices, **conservation agriculture** components (such as no till, crop residue retention), and cropping system diversification (including legumes or vegetables in the cereal rotation) [121]. The scenario where all options were integrated resulted in higher productivity and farmer income over current management, with a 54% increase in grain energy and a 104% increase in economic returns, including 35% lower water input and a 43% lower intensity of global warming potential [121].

New Zealand provides an interesting example of an industrialized country that applies an integral strategy including all food-system actors (primary food production, food industry, market, and governments) to improve public health nutrition by stimulating a larger proportion of vegetables in human diets, instead of ultra-processed food. In this case the starting point was not the end-consumer, and incentives were instead sought at the food industry level [119]. This strategy follows a three-step approach by (i) analyzing the availability and affordability of (healthy) food, (ii) identifying the determinants of food availability and affordability, and (iii) developing a food system intervention. In the above examples the challenge is to realize diversification in food production and to organize access to diverse foodstuffs, preferably fresh vegetables including legumes. Incorporating legumes in crop rotation is gaining increasingly attention, either as monoculture or as intercropping or in mixed cropping stands. Intercropping and mixed cropping (cereal–legume mixtures) enhance both diversification for human food consumption and resilience at the crop systems level [123].

Plant breeding should be part of the systems approach by developing cultivars from the concept of resilience to achieve 'flexible' cultivars that can respond rapidly to varying growing conditions caused by more unpredictable weather patterns. For example, it was shown that, under optimal growing conditions with regular rainfall or irrigation, no extensive roots were formed in lettuce, but there was genetic variation for the ability to develop more roots as soon as drought occurred [124]. Plant breeders are only recently discovering the value of improving crops for belowground traits by addressing root systems and their interactions with beneficial soil organisms that can enhance the efficiency of nutrient acquisition as well as tolerance to biotic and abiotic stresses [125,126]. In addition, breeding concepts such as population

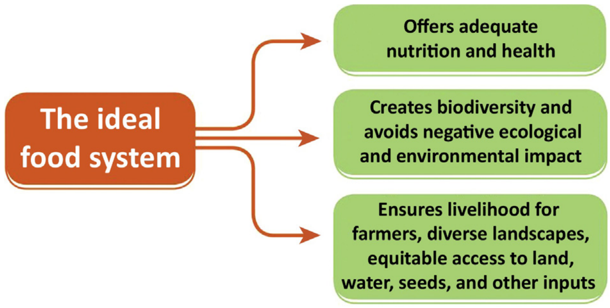


Figure 1. The Key Attributes of a Sustainable Food System (Redrawn after Sukhdev *et al*. [131]).

breeding or cultivar mixtures can enhance resilience at the systems level through diversification strategies and improve both yield and stability [71,75,123]. To better support diversified farming systems more attention needs to be given to breeding for competitive ability of crop species in intercropping and mixed cropping systems because breeding for monocultures does not automatically result in optimal plant–plant interaction in crop mixtures [127,128].

In a systems approach, access to both diverse food and diverse seeds is important. Access to seed as a source of our food is also endangered because this is nowadays to a large extent under the control of very few multinational companies [129]. Their business model is to increasingly rely on protection of their breeding activity via patenting, and they not always allow farmers to save seed on-farm or select within those seeds. Patents, in contrast to breeders' rights (including the breeders' exemption – the right to utilize each other's genotypes for further crop improvement), restrict free exchange among breeders that would otherwise maintain a broad genetic base to permit innovation across the whole breeding sector to support food security. Hence, the ownership of seed and seed sovereignty are issues affecting secure sustainable food production [130].

Adopting a systems approach to food can help in identifying, analyzing, and resolving trade-offs between nutritional, social, economic, and environmental objectives and constraints [46]. However, food systems must meet consumer food quality and safety demands, develop effective value–chain linkages, and reduce pressure on ecosystems while increasing their resilience. The three key attributes of a sustainable food system are as shown in Figure 1 [131].

Concluding Remarks

Diversifying food systems and diets improves human health and contributes to other multiple benefits including healthy ecosystems. The evidence to date suggests that biodiversity is crucial to human health and wellbeing, and adopting a food-based dietary diversity strategy has social, cultural, economic, and environmental benefits [132,133]. Promoting an enabling environment is crucial for realizing such dietary diversification that requires behavioral change interventions. Awareness campaigns to fulfill such an aim [134] should be included in a food diversification strategy, and this will require a better understanding of related factors to establish multi-stakeholder collaboration for scaling up and achieving impacts in human health through nutrition at a country level.

Reducing the environmental impact of agriculture and improving food nutritional quality will need innovative methods to produce food and will consequently require innovative plant breeding programs. There is no single or easy solution to address food and nutritional security

Outstanding Questions

How to test the hypothesis that there is a direct relationship between resource-efficient uptake of nutrients, root architectures, the ability to collaborate with beneficial soil microorganisms, and the nutritional composition and value of food crops?

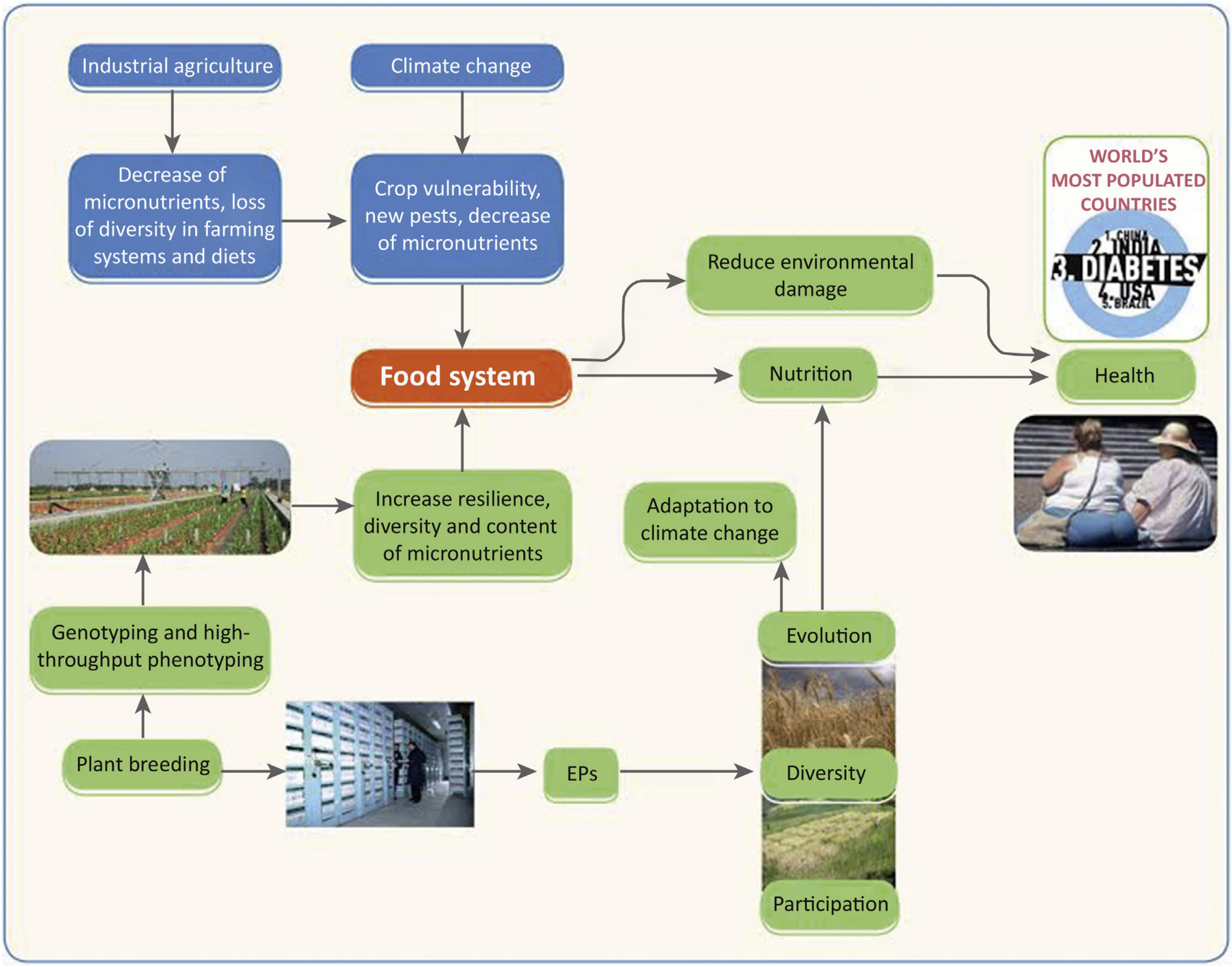
The International Union for the Protection of New Varieties of Plants (UPOV) accepts only distinct homogeneous and genetically stable lines, and not evolving populations. Why is it that the registration systems of UPOV or similar organizations, which evolved towards accepting only pure lines, do not now change to include heterogeneous cultivars (i.e., a population of genotypes) that enhance both the resilience of farming systems and the nutritional value of human diets?

What are the best avenues of transdisciplinary research to pursue, and modeling tools to use, to address the multilevel and multisectoral complex interrelationships between agri-food, human health and disease, and ecosystems, with the aim of assisting effective designs by both policymakers and scientists?

Who must increase their investments in plant breeding programs to improve nutrition-rich crops (other coarse cereals, legumes, vegetables, roots, tubers, fruits) to make them a viable alternative to maize, rice, and wheat (that now provide ~42% of calories in the human diet), thus diversifying and developing healthy agro-ecosystems to feed the world?

How to counteract the extreme market concentration (and thus the dependency on a few companies) when it is very unlikely that seed companies will replace farmer seed networks in the next decades? Farmers can produce their own seed from evolutionary populations, a practice that at several sites in the developing world generates ~90% of the seed that farmers sow.

How to transform large-scale industrialized monoculture food production back to more diversified cropping systems and local food supply?



Trends in Plant Science

Figure 2. Relationships Between Climate, Agriculture, and Plant Breeding (Including Evolutionary Populations, EPs) and Their Effects on Agrobiodiversity, Food, and Health.

while achieving environmental sustainability. Agriculture, health, and nutrition are interconnected, dynamic, and multifaceted (Figure 2). An approach is needed wherein nutritionally enhanced and resource use-efficient crops, together with integrated natural resource management, can minimize the adverse impact of climate change on agriculture. There is a need to identify and adopt dietary patterns and crop diversity that lower the environmental impact and enhance health. Production systems based on the use of heterogeneous cultivars contribute to the diversity of diets and hence to improved human health and wellbeing. Because food is a complex matrix, we suggest a holistic approach to capture the complexity of nutrition in relation to human health. Policies that encourage the adoption of healthy diets, in addition to identifying dietary patterns with lower environmental impact, combined with promotion of more active lifestyles, is a positive strategy to enhance public health (see Outstanding Questions).

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