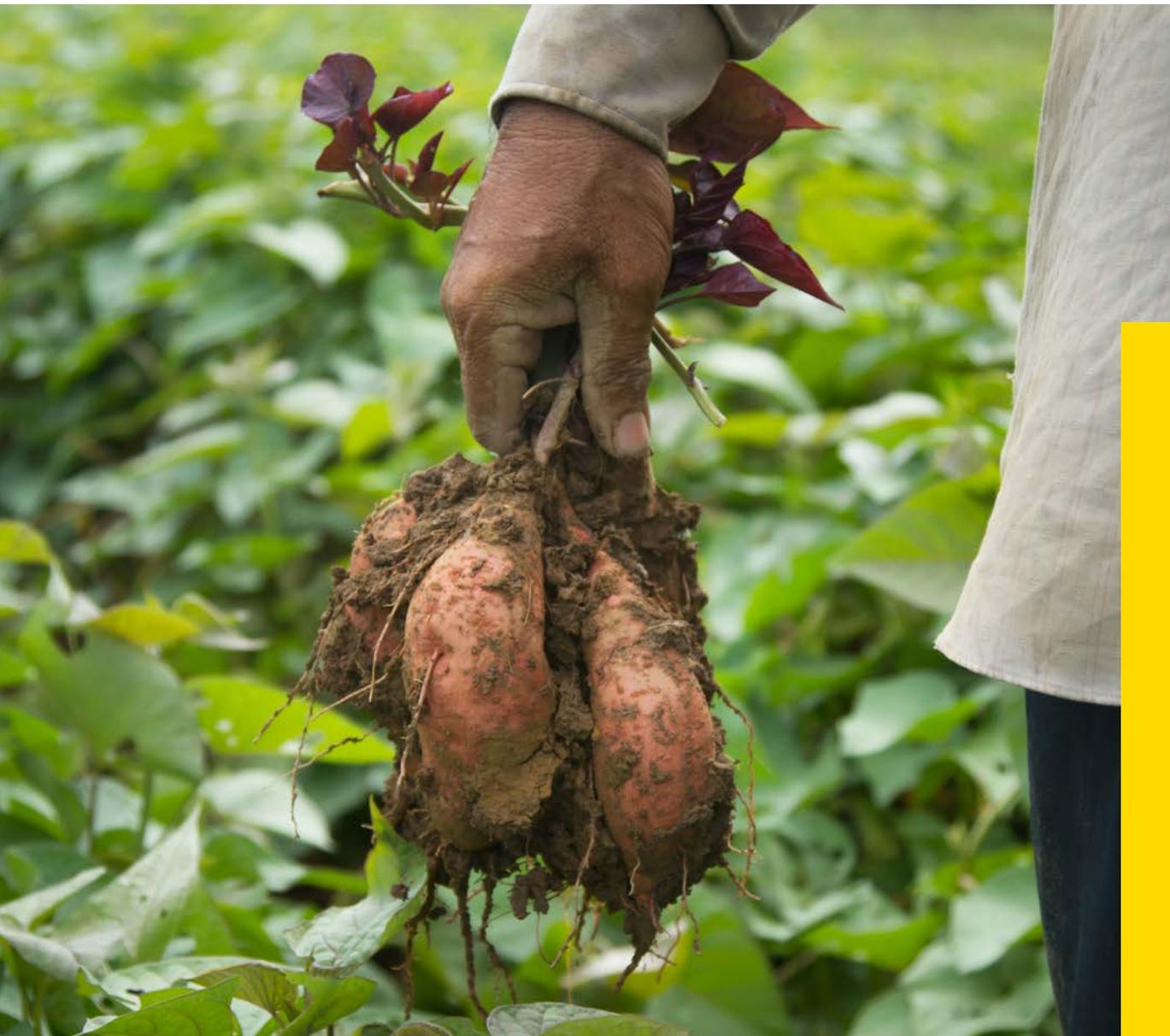


Food Science and Technology Solutions to Improve Food and Nutrition Security:

Advancing the Use of Underutilized and Biofortified Crops

Published by Institute of Food Technologists



About IFT

The Institute of Food Technologists (IFT) is a global organization of more than 11,000 individual members from 95 countries who are committed to the science of food. The primary mission of IFT is to connect global food systems and technical communities to promote and advance the science of food. Science is essential to creating a global food supply that is sustainable, safe, nutritious, and accessible to all.

EXECUTIVE SUMMARY

For over 80 years IFT has engaged experts in food science and technology and related disciplines from academia, government, and industry to help solve many of the world's greatest food-related challenges. IFT's vision is for a world where science and innovation are connected and universally accepted as essential to improving food for everyone and the mission is to connect the global food system communities to promote and advance the science of food and its application.

In 2021, IFT formed the Food & Nutrition Security Steering Committee (FNSSC) to help identify key challenges in food and nutrition security and elevate food science and technology solutions. In 2023, the FNSSC hosted their third virtual roundtable discussion on "Food Science and Technology Solutions to Advance the Use of Underutilized and Biofortified Crops" on October 30 – 31. The goal was to identify current challenges, solutions, and opportunities for food science & technology to accelerate the adoption and use of underutilized and biofortified crops to improve food and nutrition security.

Numerous nutritional, economic and planetary benefits of underutilized and biofortified crops were identified, including improved nutrient density, dietary diversity, climate resilience, fewer soil inputs, income generation and elevation of indigenous knowledge. Food science and technology can play a pivotal role in realizing these benefits by creating an enabling environment for the enhanced use of biofortified and underutilized crops across the global food system. Mainstream integration of these crops into the food supply can create wider demand and consumer awareness. This benefits smallholder farmers by providing an income stream in addition to a source of nutrition and extends the nutritional and sustainability benefits beyond local farms to global consumers. Advances in food science & technology coupled with the elevation of indigenous knowledge can also help identify the best practices and processes that can preserve the nutritional value of these crops as they are converted to foods.

Several challenges remain that need solutions to advance the use of these highly nutritious crops in global food systems. Because of their limited use, there has been less scientific research into the physical, chemical, and structural properties of these crops, as well as limited information on their potential health benefits. Additionally, a lack of policy support and supply chain development further

limits the growth and availability of many of these crops. Changing consumer demographics, tastes, and health preferences pose both a challenge and opportunity. Growing urbanization is increasing the demand for healthier, convenient foods, but consumers may be less familiar and accepting of the different flavor and texture profiles of foods made from biofortified or underutilized crops.

With these challenges and opportunities in mind, several success stories were discussed, and opportunity areas identified where food science and technology can play a critical role in increasing the adoption of biofortified and underutilized crops, including:

- improving and maintaining the nutritive value of underutilized and biofortified crops through processing
- expanding clinical research examining the impact of processing and the food matrix on bioavailability and health
- understanding the needs of consumers and changing global demographics
- collaborating with stakeholders across the food and public health system

Underutilized and biofortified crops have tremendous potential to improve food and nutrition security around the globe. Food science and technology holds the key to unlocking their full potential for the health and well-being of people and planet.

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There is a sense of urgency for us to lean into highly nutritious and climate resilient crops. We need to unleash the potential of these crops to address food security around the world. It's not a nice to do, it is a must do.

”

Alyson Greenhalgh-Ball



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Virtual roundtable discussion, “Food Science and Technology Solutions to Advance the Use of Biofortified and Underutilized Crops”

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Panelists:

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Table of Contents

IFT Food & Nutrition Security Steering Committee (FNSSC).....	4
Introduction	6
Underutilized Crops.....	7
Benefits and Challenges for Underutilized Crops	8-10
Biofortified Crops	11
Benefits and Challenges for Biofortified Crops	12-14
The Role of Food Science and Technology in Increasing the Use of Underutilized and Biofortified Crops.....	15
Case Study 1 – Application of indigenous knowledge into modern processing	16
Case Study 2 – Orange Flesh Sweet Potato	17-18
Case Study 3 – Improving acceptance of underutilized crops by mainstream consumers	19
Case Study 4 – Improving zinc retention in parboiled biofortified rice.....	20
Case Study 5 – Creating private sector demand through public-private partnerships	21
Continued efforts and future opportunities for food science and technology.....	22
Improving nutrition through processing	22-23
Expanding clinical research on bioavailability, biomarkers, and health benefits	24-25
Increasing sustainable processing practices and technology transfer and training globally.....	25-26
Understanding the needs of the consumer and changing demographics	27-28
Collaborating with stakeholders across the food and public health system.....	29
Conclusion	30
References.....	31-35

INTRODUCTION

In 2015, the United Nations established 17 sustainable development goals (SDG) to achieve by 2030 and food and agriculture play an instrumental role in accomplishing these goals, particularly zero hunger (SDG 2), good health and wellbeing (SDG 3), responsible consumption and production (SDG 12), and life on land (SDG 15). Eliminating global hunger has been a pressing issue even before the establishment of the SDGs, and the global expansion of high-yield commodity crops in the last half of the 20th century helped dramatically reduce hunger globally (1, 2). However, as global hunger declined, micronutrient malnutrition came into focus. The reliance on commodity crops had increased the availability of calories globally, but agricultural and dietary diversity had declined as many traditional, nutrient-rich crops became underutilized in favor of commodity crops (2, 3). The concern transitioned from food security to also include nutrition security.

To address the growing issue of micronutrient malnutrition, commonly referred to as “hidden hunger,” the food and agriculture sectors began to pivot in the 2000s toward large scale micronutrient fortification, the development of biofortified staple food crops, and increased use of underutilized, nutrient-rich plants for enhancing dietary diversity (2, 3). Further fueling these efforts was a growing awareness of the potential impact of climate change on food security as many underutilized plants are often naturally climate resilient. Additionally, there were growing concerns about the long-term environmental sustainability of continued expansion of high-input commodity crops.

Today, as the 2030 deadline for the SDGs approaches, there is a renewed urgency to ensure sustainable food and nutrition security for a growing global population within the constraints of limited resources and a changing climate. While efforts across the entire food system are necessary, advances in food science and technology, from processing to distribution and delivery to the consumer, play a critical role in achieving the SDGs. Mainstream integration of biofortified crops or underutilized crops into food systems will require processing solutions to allow for greater use of these crops in foods as well as development of foods that are acceptable and affordable for consumers. Additionally, these technologies must have minimal impact on the environment and ensure that the nutritional benefits of the crop are retained through processing and storage to be delivered to the consumer.

This white paper summarizes a roundtable discussion that identified food science and technology challenges, opportunities, and solutions to advance the use of biofortified and underutilized crops. These solutions highlight the role of food science and technology in helping to achieve food and nutrition security around the world while also considering sustainability, consumer acceptability, and availability, accessibility, and affordability for all.



Underutilized Crops

It is estimated that as many as 30,000 plant species across the globe are edible, yet only 170 plants are currently cultivated for food on a commercial scale and 60% of calories consumed worldwide come from 4 crops – rice, corn/maize, wheat, and potato (solanum type) (1, 4). Thus, thousands of edible plants are underutilized and have the potential to contribute to nourishing the world. Underutilized crops are typically wild or semi-domesticated plants that are grown and adapted to native regions, but have been marginalized for multiple agronomic, economic, and cultural reasons (3, 5). They are also sometimes referred to as neglected, orphan, minor, promising, or little-used crops. Examples of some of these plants are in Table 1.

Underutilized crops:

Wild or semi-domesticated plants that are adapted to particular environments, but receive little attention from researchers, plant breeders, food processors, or policymakers. These plants are not traded as commodities and much of the knowledge of their cultivation and use is limited to local cultures.

Table 1. Examples of underutilized crops.

Grains and Pseudocereals	Legumes/Pulses	Roots/Tubers	Fruits/ Vegetables	Nuts and Seeds
<ul style="list-style-type: none"> • Millets (<i>pearl, finger, foxtail, proso, kodo, little, barnyard, etc.</i>) • Sorghum • Fonio • Teff • Buckwheat 	<ul style="list-style-type: none"> • Bambara groundnut • Grass pea • Black/green gram • Pigeon pea • Marama bean 	<ul style="list-style-type: none"> • Yams (<i>purple, fancy, elephant’s foot, etc.</i>) • Mashua tuber • Yan bean • Taro • Arrowroot 	<ul style="list-style-type: none"> • Bayberry • Chayote • Indian gooseberry • Baobab • Roselle • American Elderberry • Pawpaw 	<ul style="list-style-type: none"> • African walnut • Black walnut • African breadnut • Mongongo nut • Perilla • Linseed (flax)

Benefits and Challenges for Underutilized Crops

Many underutilized crops are of high nutritional value, containing micronutrients, protein, and dietary fiber, and have been grown in less technologically developed regions of the world. As a result, they are typically very hardy plants that thrive in poor resource environments, such as arid areas with high temperatures and low rainfall, and are more resistant to biotic stresses, such as fungi and insects (Table 2). This climate- and pest-resilience has increased global interest in these plants in contrast to commodity crops which often require greater environmental inputs (e.g., water, fertilizer, pesticides, etc.). Further, for some parts of the world, underutilized crops can become the only food source when commodity crops fail due to drought, pests, or other stresses.

Underutilized crops are also highly valued in traditional food cultures and often have an extensive culinary heritage among indigenous populations. Many of these indigenous communities, particularly the women in these communities, are the caretakers of these crops and have most of the knowledge of how to grow, cultivate and prepare these plants for consumption (5, 6). As the interest in these crops grows, recognizing and respecting the value of this traditional knowledge can empower indigenous people and women.

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Not only are these crops good for helping us to mitigate climate change, but they bring the voices of marginalized communities and women who are the custodians of these crops. Bringing greater attention to underutilized crops brings greater attention to the voices that have not been heard within the global food system.

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Tawanda Muzhingi

Table 2. Benefits and challenges for the use of underutilized crops.

Potential Benefits	Challenges
<ul style="list-style-type: none"> • Nutrient density (<i>micronutrients, protein, fiber</i>) • Hardy crops, evolutionarily adapted to harsher environments (less water, poor soil, etc) so require less inputs in such conditions • Naturally more resistant to abiotic (<i>drought, heat, etc</i>) and biotic stresses (<i>fungi, insects, etc.</i>) • More genetically diverse than commodity crops which can enhance resilience • In many areas, still traditionally consumed and culturally relevant • Empowerment of indigenous communities and women that are the primary growers/cultivators of these plants 	<ul style="list-style-type: none"> • Typically grown on a small scale and consumed by small local population • Inadequate research on cultivation, post-harvest processing, and nutritional benefits • Lower yield per crop cycle compared to commodity crops (although some have multiple crop cycles per year) • Lack of public policy support for their cultivation and expansion In many areas, still traditionally consumed and culturally relevant • Poorly developed value chains and inconsistent supply • Lack of economic viability for income generation • Lack of modern processing technologies to create value-added foods • Different colors, flavors, and textures may be less acceptable to consumers used to milder commodity crops • Stigma of being “foods of the poor”

Despite these potential benefits there are several factors that create challenges for increasing the use of underutilized crops (Table 2). Generally, they have lower yields and poorly developed value chains which make them not economically viable for farmers to grow for income generation. For example, yields per hectare of maize are double or triple that of millets, an underutilized crop, even when grown in fertile areas with adequate rainfall and fertilization (8, 9). However, millets can often yield more than one harvest due to their short growing cycle. Many of these crops are grown on small shareholder farms and in small quantities so more land can be used for cash crops. There is also considerable variability in the seeds and growing practices for the same crops on different farms, so the quantity and quality of the supply is inconsistent, as well as the nutritional content. Additionally, a focus of public policy initiatives and incentives promoting commodity crops has overshadowed underutilized species. This has resulted in some very promising crops having little or no genetic or agronomic development. For example, marama beans, indigenous to the Kalahari Desert, are drought resistant and comparable nutritionally to soybean and peanut, but due to their long maturation time (~2 years), they have not been agronomically developed and grow only in the wild, although there are efforts to increase their cultivation (10).

The lack of agronomic development often leads to a lack of food science and technology development that results in challenges of scale and consumer acceptance. Most scientific research and advances in food processing have focused on commodity crops which creates manufacturing challenges when trying to include alternative, underutilized crops in foods. For example, in India, most grain processing plants are set up for wheat and rice which has created hurdles for the incorporation of underutilized crops, such as millets, into foods. Additionally, the considerable variation even within a single type of crop (e.g., millets have different genotypes and phenotypes, but are broadly grouped as one crop) creates challenges when current processes and nutrient labeling are set up for highly uniform commodity crops. The continuing loss of traditional knowledge on how to prepare these crops for food, the lack of understanding of the sensory characteristics of these crops, and the lack of clinical data supporting health benefits (and the impact of processing on these benefits), also present challenges for consumer acceptance.



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With underutilized crops we are in a race against extinction. Many of the cultures that know how to use and process these crops are dying out and if we don't preserve this knowledge, these crops and how to eat them may cease to exist.

John Taylor

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In many countries, people have forgotten how to eat underutilized crops.

”

Shauravi Malik

Culturally, there has also been a stigmatization of underutilized crops as the “foods of the poor”(5, 7) and it is often a sign of progress to be able to avoid foods that are evocative of poverty. With increasing urbanization and even rural cultures eschewing traditional crops in favor of cash crops, the local technical knowledge of how to grow, cook and consume underutilized crops is disappearing. Within many cultures there is also a transition in dietary habits to foods made with commodity crops and underutilized crops are often not easy to substitute into these now familiar foods. For example, leavened, loaf-type wheat bread has become a staple in some parts of Africa even though wheat has to be imported because it is not grown in many African countries. Consumers prefer the sensory aspects of wheat bread, but many indigenous grains, such as millets or sorghum, do not contain gluten and are poor substitutes for refined wheat in leavened, loaf-type breads.

Overall, underutilized crops hold great potential to increase biodiversity, address issues of hidden hunger, and encourage sustainable agricultural practices. They also can enable equity by preserving the culinary heritage and cultural food ways of local regions and elevating the women and small shareholder farmers that are the curators of these crops. However, there are several agronomic, technological, nutritional, and cultural challenges that must be overcome. Food science and technology can help address many of these challenges and will be further discussed in the sections below.



Biofortified Crops

Micronutrient fortification of foods has been around for many decades in developed countries, and has expanded to many low- and middle-income countries to help address micronutrient deficiencies. While this effort has been one of the most successful and cost-effective public health initiatives, there remain challenges in the continued global expansion of fortification, including a lack of technological and economic capacity as well as a lack of regulations and enforcement (11). Additionally, rural, subsistence populations that cannot afford or don't have access to fortified foods, still struggle with micronutrient deficiencies. In the 1990s, a new strategy of biofortification emerged that aimed to increase the inherent micronutrient content of staple crops through conventional breeding, agronomic practices, or genetic engineering (12, 13). Focused primarily on vitamin A, iron, and zinc (the micronutrients most associated with global burden of disease), more than 240 biofortified crop varieties are now grown in approximately 35 countries and consumed by more than 40 million people (13, 14). Some examples of these crops are included in **Table 3**.

Table 3. Examples of biofortified crops.

<p>Vitamin A</p>	 <p>Sweet Potato</p>	 <p>Cassava</p>	 <p>Maize</p>	 <p>Banana/ Plantain</p>
<p>Iron</p>	 <p>Beans</p>	 <p>Pearl Millet</p>	 <p>Cowpea (+zinc)</p>	 <p>Sorghum (+zinc)</p>
<p>Zinc</p>	 <p>Rice</p>	 <p>Lentil (+iron)</p>	 <p>Wheat</p>	 <p>Potato (+iron)</p>

Benefits and Challenges for Biofortified Crops

Biofortified crops were developed primarily as a nutrition intervention to complement fortification and supplementation efforts in targeted populations with inadequate access to diverse diets, fortified foods, or micronutrient supplements (13). Because staple crops are the primary source of energy for many of these populations, augmenting these already nutritious crops with additional nutrients of need is an effective way to elevate their intake of critical micronutrients. In fact, several studies have demonstrated benefits of biofortified crops for nutritional status and health outcomes, such as cognitive function and child morbidity (13).

Since adoption of improved varieties is generally limited in low input cropping systems, most biofortified varieties were developed with agronomic competitiveness such as yield advantage, resistance to diseases or stress tolerance (15). Biofortified varieties with high content of iron or zinc, such as wheat and rice, can be used within existing value chains rather than creating new value chains (Figure 1). These crops are also more likely to be accepted by farmers and consumers since they are grown with similar inputs and generally have higher yields to non-biofortified versions and are easier to incorporate into existing local diets (13). For biofortified crops with high provitamin A carotenoids which provide a yellow or orange color to the crop, consumer preference is mixed based on local context (16). A few of the crops that have been targeted for biofortification have also been identified as underutilized, such as millet (iron biofortified pearl millet) and sweet potato (orange flesh sweet potato). These biofortified versions of underutilized crops often retain many of the benefits of the traditional varieties, such as sustainable agronomic practices, climate resilience, and opportunities to elevate of indigenous populations and women.

Biofortified crops are also cost-effective for the benefits they provide (17). While there is considerable investment in the initial development of these crops through breeding or biotechnology, once established, the nutritional traits of the crop are stable and with appropriate breeding schemes and agronomic practices, should yield consistent crops with enhanced nutritional value without recurrent costs.

Figure 1. Value chain for biofortified crops is similar to conventional crops. Adapted from (18)



Over time, it has become apparent that to continue to increase the use of biofortified foods, wider integration into the food system is necessary, and this brings many challenges (Table 4) (18). Because biofortified crops were designed primarily for the nutrient needs of subsistence farmers in developing countries, the potential impacts of expanding the use of these crops in the broader food system have not typically been considered. In particular, research examining the impacts of industrial processing on the nutrient content, retention, and bioavailability of biofortified crops has lagged behind agronomic development and nutritional studies. Many nutritional efficacy and effectiveness studies assume retention through storage and food processing without actual testing, which may over- or underestimate actual intake of the nutrient of interest. Proper understanding and interpretation of apparent vs. true nutrient retention is also needed. Apparent retention represents the nutrient concentration (amount of nutrient/unit mass) in the final food relative to the harvested crop and is important for food processors to understand the nutrient content of their food for labeling purposes or claims. True retention also compares the nutrient content before and after processing but takes into account physical losses through processing (amount of nutrient/unit mass X mass). This is useful for policy makers to identify the most effective processes to deliver more nutrients to target populations with minimal loss. Further, for some nutrients, particularly zinc, there is a lack of standardized and reliable biomarkers of status and bioavailability to determine the efficacy of these crops in meeting nutrient needs.

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Most biofortification efforts have been led by agronomists and nutritionists and we need to introduce the angle of food science and technology to help with the understanding of the impacts of processing. In many cases, not understanding the impact of processing on nutrient retention can drastically impact the outcome of nutritional studies.

”

Victor Taleon

Table 4. Benefits and challenges for increasing the utilization of biofortified crops

Potential Benefits	Challenges
<ul style="list-style-type: none"> • More access of micronutrient-rich foods for populations in greatest need for the micronutrient • Some are traditionally underutilized and carry benefits, such as low input needs, resilience, and familiarity with consumers • Economic opportunities for small, medium, large food processors to develop nutritious foods with biofortified crops • Agronomic practices similar to conventional crops so more acceptable to farmers • Most can be substituted for conventional crops in existing value chains • Cost-effective nutrition intervention requiring low resources beyond initial breeding investment 	<ul style="list-style-type: none"> • Concerns that increasing adoption of biofortified staple crops could exacerbate a lack of dietary diversity in some populations • Preserving the safety of harvested food when some crops have to provide year-round nourishment • Insufficient research and understanding of the effect of processing on nutrient retention • Inadequate biomarkers for some nutrients that hinder effectiveness research • Different colors, flavors, and textures may be less acceptable to consumers used to milder commodity crops • Concerns that increasing use by food processors will hinder farmers from using the crops to feed their families

Policy and regulatory challenges as well as societal implications of increasing market utilization of biofortified crops has also limited expansion in the food system. There are few regulations and standards for biofortified crops, thus limiting the uptake from food manufacturers for use in foods (18). There are also concerns that growing demand for biofortified crops for use in foods in urban markets will result in small shareholder farmers selling more of their biofortified crops instead of saving them for their family to consume. Addressing these challenges will require a multi-sector approach that includes food science and technology solutions to enable the production of foods that are nutrient dense, affordable, accessible, and acceptable to consumers, while preserving farmer livelihoods and health.



The Role of Food Science and Technology in Increasing the Use of Underutilized and Biofortified Crops

While the agronomy and public health nutrition sectors have provided much of the stimulus to expand the use of underutilized and biofortified crops, food science and technology has made significant contributions to create an enabling environment for the enhanced use of these crops in foods. To increase utilization of these crops, it is necessary to create wider demand in the food system, which is a key focus of the Sustainable Development Goal 2 (SDG2) Advocacy Hub, Food and Agriculture Organization (FAO), International Food Policy Research Institute (IFPRI)/Harvest Plus, and others (3, 18-20). This benefits the farmer by providing an income stream in addition to a source of nutrition and can extend the nutritional and sustainability benefits of these crops beyond the farm into urban areas and globally. Food science and technology enables this process by:

- Developing and adapting technologies to incorporate these crops into familiar foods in the market
- Designing foods that are acceptable and affordable to consumer
- Identifying processing techniques to best preserve nutrient content
- Identifying best practices to minimize post-harvest loss of nutrients
- Researching the functional properties of different crops to de-risk their use and incentivize further investment in the development of foods made with these crops
- Enabling the transmission of indigenous knowledge into modern processing techniques

Expanding the use of these crops is particularly critical as increasing urbanization moves individuals further from their food source and increases reliance on convenience foods made predominantly from commodity crops. Providing greater diversity in local and global markets has the potential to significantly improve food and nutrition security. The following case studies demonstrate how food science and technology has already created an enabling environment for the increased utilization of these crops.

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While creating demand from the consumer for these crops is, to some, the first goal to strive towards, having an enabling environment is equally important and food science plays a critical part in that environment. There is no point in creating demand if we can't meet that demand with great science and understanding of the technical solutions needed.

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Alyson Greenhagh-Ball

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Case Study 1

Application of indigenous knowledge into modern processing

It is critical as food science and technology continues to try to mainstream underutilized crops that the knowledge contained within the cultures that traditionally have used this crop for food be preserved and transmitted into broader practice. This respects the cultural importance and traditions of local populations and provides tremendous insights into best practices for processing and preparing these crops into nutritious, culturally-relevant foods.

An example already in practice is the development of mills to process millets and sorghum. Due to their small size, millets are often considered difficult to process in traditional mills made for larger grains, such as wheat and corn. However, a group of researchers examined the methods and equipment used by local women in Tanzania to hand grind millet for use in foods (21). It was determined that the use of a large mortar and pestle, along with the technique of twisting along with pounding was highly efficient in producing a product acceptable to the local population. This information was then used to design mills that incorporated pounding and twisting instead of the traditional abrasive milling that resulted in lower yields (22) (Figure 2).



Figure 2: Application of indigenous knowledge on millet processing to industrial scale. Photo from Dr. John Taylor.

Additional examples of indigenous knowledge include the use of underutilized grains and tubers in flatbreads, such as Injera, Dosa and Idli, in India and parts of Africa. Local populations have discovered that processes such as sourdough fermentation, using batters instead of doughs, using steam during baking, and blending grains and tubers can yield a desirable product. Food scientists have used this knowledge to innovate and adapt these techniques for larger scale production.

These approaches should continue to be used to elevate the importance and relevance of indigenous knowledge and apply it to modern technology to increase utilization. Some have also suggested that intellectual property rights and licenses should be offered to marginalized groups to give appropriate credit to the populations that hold this indigenous knowledge.

Case Study 2

Orange Flesh Sweet Potato

Orange flesh sweet potato (OFSP) is a biofortified crop grown in several African countries that provides a source of Vitamin A to populations that are at risk of, or have, Vitamin A deficiency. White flesh sweet potato has been traditionally consumed throughout Sub-Saharan Africa and is critical for food security since it is a low-input, short-cycle crop that is climate resilient. However, it has low nutritional value and is generally underutilized due to the stigma of being a “food of the poor.” Orange flesh varieties were developed to provide greater nutrient density and address micronutrient malnutrition.

The growing urbanization across Africa as well as younger consumers preferring healthier and more convenient food options created a market opportunity to use OFSP as an ingredient in a wider variety of products. To enable wider market use, food scientists evaluated the use of OFSP in foods such as bakery products (**Figure 3**), leading to the following findings:

- OFSP puree retains more than 95% of the beta-carotene
- Incorporation of OFSP puree in wheat bread provides a meaningful amount of beta-carotene to help combat vitamin A deficiency (23)
- Using the puree in bakery products enables reduction of refined sugars and fats
- OFSP puree alters the starch digestion when incorporated into wheat bread which may lower the glycemic response, offering additional health benefits (23)



Figure 3: Loaves of bread with orange flesh sweet potato puree (Photo from Dr. Tawanda Muzhingi)

Orange Flesh Sweet Potato

These food science achievements enabled market system approaches to integrate OFSP puree as an ingredient in baked goods across many countries in Africa, including Kenya, Uganda, Malawi, Rwanda, and Ethiopia. Multiple benefits across the food system have been identified:

- Farmers cite economic and health benefits as the key drivers for adoption of OFSP with the economic benefits including the ability to invest income on housing, livestock, food, and land (24).
- Households growing OFSP experience an increase in food consumption and food security, which is more pronounced in women-headed households than men-headed households (19).
- Women express greater self-esteem with increased income to buy consumables for the household without the need to ask husbands for money (24).
 - ◊ This demonstrates the importance of considering gender in market-focused initiatives as crop production is often taken over by men as commercialization develops.
- Households sell ~1/3 of their OFSP harvest leaving the majority of production for home consumption which contributes to nutrition security for farming families.
- Use of OFSP as a substitute for wheat decreases reliance on imported wheat and foreign currency.
- Involving the right partners across multiple sectors (agriculture, health, trade, education, processing) enables small to medium enterprises (SMEs) to rapidly and sustainably scale production and avoid bottlenecks (25).
- Technology transfer of food processing techniques and equipment can enhance value addition. For example, aseptic microwave packaging of OFSP puree developed in the US has been transferred to Africa and yields an ingredient with better color, beta-carotene retention, and shelf stability.
- In some markets, OFSP breads are considered a premium product, helping remove the stigma associated with “food of the poor” and appealing to the aspirational values of the urban population.
- Market growth increases public and private sector investments in breeding and seed programs, further increasing smallholder productivity.

Future opportunity areas include integrating OFSP purees into culinary applications at restaurants and institutional kitchens, developing OFSP varieties best suited for making purees, enhancing quality control in the supply chain, and developing standards for biofortified varieties and products.



Case Study 3

Improving acceptance of underutilized crops by mainstream consumers

Millets and lentils have traditionally been consumed throughout India but increasingly urban consumers are moving away from millets and lentils to convenience foods made with commodity crops. As consumer preferences and behaviors shift, there is a risk of losing the skills, knowledge and liking for traditional grains and legumes. In 2016, three friends (and parents) united with the goal to improve the foods offered to children in India by creating healthy, tasty, and affordable products made with traditional, nutritious millets and lentils. Today Wholsum Foods offers a wide range of ready-to-eat foods, snacks, noodles, and ready-to-cook grains for children under two brands, Slurrp Farm™ and Mille.

One of the key challenges the company faced was consumer acceptance. Millets and legumes have different taste and texture profiles as compared to rice and wheat which are more commonly used in children's foods. To address this challenge, Wholsum Foods worked with food technologists to evaluate traditional methods and ingredients of preparation of millets and legumes to find tastes and textures which appealed to customers today. For example, the use of jaggery as a sweetener is common in traditional preparations of millets and lentils and can improve taste. As an unrefined source of sugar, it has a more molasses-like taste and less was needed to sweeten a food compared to white sugar. Jaggery also contains small amounts of minerals such as calcium and iron not present in refined sugars (26).

Additional solutions that helped consumer acceptance was the use of grain blends for texture and flavor and using familiar foods such as puffs, dosa, pancakes, and noodles to improve consumer awareness and willingness to try foods with these grains and legumes. A focus on children's foods through their brand Slurrp Farm™ helps introduce underutilized grains such as millets at a young age to help growing children adjust to the taste and improve acceptance into adulthood.



Images from Wholsum Foods

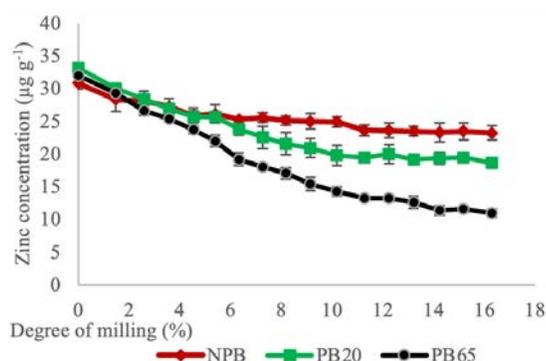
Case Study 4

Improving zinc retention in parboiled biofortified rice

Parboiling is a common processing technique that involves soaking, steaming, and drying paddy-rice to create a harder kernel that breaks less during milling. Parboiling typically improves the nutritional content of milled rice since the heated water promotes migration of vitamins and some minerals found in the outer layers of the kernel into the endosperm. However, zinc concentrations in biofortified and non-biofortified rice varieties, have been shown to be lower in parboiled compared to non-parboiled rice (27). Researchers at HarvestPlus investigated the reasons for this loss of zinc to identify process improvements that may be able to help preserve zinc content, particularly in biofortified rice (28).

After investigating multiple parboiling conditions and degrees of milling, the researchers determined that soaking the rice at high heat (>60°) compared to room temperature, resulted in greater migration of zinc from the endosperm into the outer layers. During the soaking step, any zinc in the outer layers would bind to phytic acid and was subsequently removed during the milling process. The degree of milling was also critical as more intense milling resulted in greater loss of zinc (Figure 4) (28).

Figure 4: The effect of different parboiling and milling conditions on zinc concentration in a variety of zinc-biofortified rice. NPB = non-parboiled; PB20 = parboiled rice soaked at 20°C for 24 h; PB65 = parboiled rice soaked at 65°C for 4 h. From (28)



As a result of this research, recommendations were made for optimal soaking temperature and degree of milling to ensure zinc levels meet intake recommendations for children who consume rice as a staple food. This research also helped inform breeding targets for zinc in biofortified rice.

Future studies are needed to examine the bioavailability of zinc in parboiled rice due to binding with phytic acid. Additionally, as consumers prefer highly polished (slender) rice, raising awareness of the nutritional benefits of more moderate polishing for parboiled rice is needed.

Case Study 5

Creating private sector demand through public-private partnerships

To accelerate the development of underutilized crops, there is a need to incentivize and de-risk private sector investment, and public-private partnerships (PPP) is one way to achieve this goal. The Foundation for Food and Agriculture Research (FFAR), established by the United States Farm Bill in 2014 to develop PPP in food and agriculture, partnered with the Global Alliance for Improved Nutrition (GAIN) and the Rockefeller Foundation to initiate the Harvest for Health Challenge (29). The goal of the Harvest for Health Challenge is to identify functional ingredients in underutilized crops to enhance their market potential.

Prior to commencing the project, members of the private sector, including food companies, were interviewed to better understand what types of functionalities or ingredients they were looking for in foods. Phase 1 (currently underway) provided competitive funding for the development of predictive models identifying functional properties of underutilized crops that could lead to the development of ingredients such as taste & flavor enhancer, thickeners, emulsifiers, stabilizers, bulking agents, and ingredients with high nutrient density. Phase 2 provides funding for selective crop development based on the results of phase 1 identifying the crops with the most potential for increased public and private sector investment.

The advantages of this PPP include:

- Cost savings and risk reduction – each dollar of funding from the private sector is matched with public funding
- A focus on actionable science with tangible solutions
- Multiple beneficiaries such as large- and small-scale farmers, food industry, consumers, environment
- Involvement from the private sector early on to determine functional properties and ingredients of interest



Continued efforts and future opportunities for food science and technology

Food science and technology solutions continue to be developed to create an enabling environment to integrate underutilized and biofortified crops into the food system. However, gaps in science, policy, deployment, and scaling of technology, and understanding of the consumer remain. Addressing these gaps is necessary to ensure the increased utilization of these crops in a safe, sustainable, and nutritious manner, that meets the needs and desires of a growing population. This will require collaborative efforts and advocacy across the food system.

Improving nutrition through processing

Foundational research on the physical, structural, and nutritional properties of many underutilized and biofortified crops is critical for understanding how these crops could be used in foods (30-32). Additionally, there continues to be a need for research evaluating the impact of various food processes and food forms on nutrient content and bioavailability. One of the concerns often raised when considering the use of biofortified and underutilized crops for foods is the impact of processing on nutrient content and bioavailability. Processing has the potential to improve bioavailability of some nutrients since many cooking processes release nutrients that are bound to “anti-nutrients” in plants, such as phytic acid or tannins, making the nutrients more available for absorption. However, processing also has the potential to reduce the nutrient content of foods, such as the milling of grains to remove bran, where many micronutrients are contained. Further, the final food matrix may also impact digestion and absorption of critical nutrients. To continuously improve the nutritional quality of foods, this fundamental knowledge of the interaction of processing and nutrition is greatly needed. PPPs, similar to the Harvest for Health Challenge by FFAR (29) and Biofortification Hub (33), could foster collaborative investments to accelerate this research and enable adoption of these crops across the food supply.

“

Trying to breed out antinutritional components, that have multiple genes involved and play an important role in plant physiology, often takes considerable time and effort. Processing can be a more viable and expedient avenue in many cases to minimize the effects of antinutritional factors.”

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Ram Ramakrishna

This type of research could also be expanded across the broader supply chain, from the field gate to the consumer, to identify areas where the greatest nutrient losses are observed and identify improvements that can be made to minimize nutrient loss and improve bioavailability. Development of rapid analytical methods that allow for faster measurement of nutrient content at various points in the supply chain would accelerate research in this area and improve traceability.

As more is learned about the impact of processing on nutritional quality, it will be critical to balance this information with cost, consumer acceptance, and food safety so that improvement in one area does not come at a substantial detriment to another. For example, some milling and polishing of grains is critical for the removal of environmental contaminants, which results in the loss of some nutrients, but is necessary to ensure food safety. Understanding these trade-offs and identifying the optimal balance of these factors should be a key objective of future research.

Food scientists should also work with agronomists at the early stages of crop development and breeding to discuss certain traits or agronomic practices that may enhance nutrition and enable processing. While breeding programs have historically given priority to yield or pest resistance, there is also a need to focus on processor and consumer preferences to increase adoption through the food system. A model for this type of interaction was recently completed for roots, tubers and cooking bananas by Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD) and also within the international centers for agricultural research within the Consortium of International Agricultural Research Centers (CGIAR) network (34-36). Soil conditions and seed variants also impact nutrient content and developing standardized practices and consistent seed supply can better ensure micronutrient content.

As previously discussed, there is often considerable indigenous knowledge on the preparation of underutilized crops for consumption. Evaluation of traditional techniques such as fermentation, sprouting, puffing, popping, or malting could yield insights on improving nutrition and consumer acceptance (37).



Expanding clinical research on bioavailability, biomarkers, and health benefits

In tandem with food science research, clinical research is needed to better understand bioavailability of nutrients in biofortified and underutilized crops as well as potential health benefits. Commodity crops have benefited from substantial public and private investment in clinical trials that should now be expanded to include biofortified and underutilized crops. It is likely that as market demand increases for these crops, investment in clinical research will accelerate as consumers desire to know more about the nutrition and health benefits of these foods and food companies explore opportunities for health and nutrition claims. This was observed with quinoa which began to grow in popularity in the early 2000s. The number of health-related studies on quinoa tripled between 2006 to 2016 and peaked in 2022 with more than 12 times as many publications compared to 2006¹.

Critical for the success of bioavailability and health benefit studies are sensitive and reliable biomarkers of nutrient status in humans. This is a need even beyond the scope of biofortified and underutilized crops and is a global initiative of major research groups, such as Biomarkers of Nutrition for Development (BOND). In particular, there is a need for a biomarker of zinc physiological status and efforts are ongoing to identify a reliable biomarker (see Box 1 for more information) (38). Emerging research also suggests the microbiota may be influenced by nutrient status and with further study may be a useful tool to identify, and potentially treat, nutrient deficiencies (39, 40).

Future studies should also examine the presence of other bioactives in biofortified and underutilized crops that may enhance the bioavailability of critical nutrients. For example, nicotianamine, a bioactive present in most plants, can chelate iron and has been shown to enhance the bioavailability of iron in biofortified grains (41). There may also be biological interactions between nutrients that are impacted by status. For example, Reed et al. (40) demonstrated a link between poor zinc status and retinol metabolism, suggesting a potential interaction of zinc and vitamin A.



“

As we move to the future of biofortification the results of the nicotianamine studies suggest that perhaps instead of focusing on the increasing the content of a specific nutrient, like iron and zinc, we could look to other bioactives that are naturally present in crops to increase the bioavailability of the nutrient of need. This may also contribute to other beneficial effects on body systems, such as the microbiome.

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Elad Tako

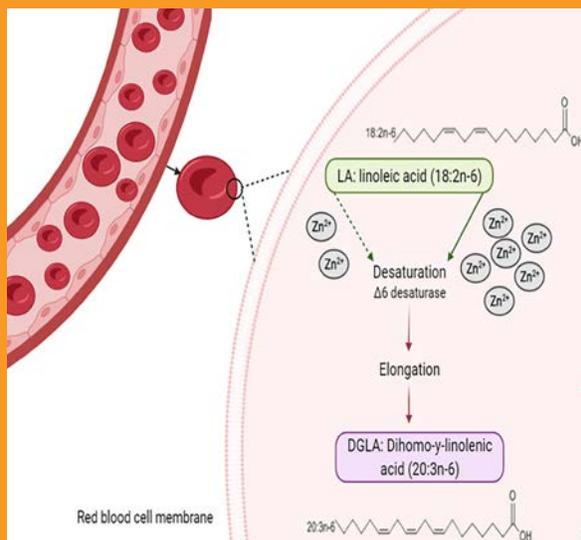
Ethnobotanical research that examines the relationship of humans and plants as they are used for food, medicine, or other applications could also provide insights and hypotheses into future health benefit research.

¹Based on search of “quinoa” in PubMed on January 13, 2024. Publications in 2006 = 24; 2016 = 77; 2022 = 298

Developing a biomarker for assessing zinc status

Currently, there is no universally accepted measure of zinc status in humans and current markers include hair, urine and plasma (38, 42). According to BOND, there is a need for a biomarker of zinc status that is more sensitive than current markers (38). A research group in the Department of Food Science and Technology at Cornell University has developed a biomarker for zinc status based on the ratio of linoleic acid (LA) to dihomo- γ -linolenic acid (DGLA) in red blood cells (Figure 5) (43). Zinc is required for the conversion of LA to DGLA by $\Delta 6$ -desaturase; therefore, low zinc status should result in an increase in the LA to DGLA ratio. Studies in animals and humans have shown the LA:DGLA to be sensitive to changes in zinc intake (43, 44). Future studies should examine the utility of this emerging biomarker in larger intervention trials and in populations with zinc deficiencies.

Figure 5: An abbreviated schematic of the linoleic acid (LA) to dihomo- γ -linolenic acid (DGLA) fatty acid pathway within the red blood cell. Lack of dietary zinc (dashed line), necessary for $\Delta 6$ desaturase function will limit conversion of LA to DGLA, resulting in an increased ratio of LA to DGLA. This ratio may be a potential biomarker to identify zinc deficiency. Adapted from (45).



Increasing sustainable processing practices and technology transfer and training globally

As most underutilized and biofortified crops are predominantly grown and consumed in the global south, it is important to ensure that food scientists, processors, and entrepreneurs in these regions have the tools and training needed to be able to produce marketable foods in a safe and sustainable way. “One-and-done” training is not enough and SMEs need continued training, as well as business support. Some organizations, such as International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and International Potato Center (CIP), have developed programs that provide business development support to enhance the effectiveness of competitiveness of SMEs marketing foods with underutilized and/or biofortified crops, but more are needed (46, 47).

Numerous innovation labs and private sector initiatives around the world are working on technology and knowledge transfer for food science, technology, and engineering. USAID Feed the Future supports more than 20 innovation labs that pair experts from the US with researchers in developing nations to improve food and nutrition security (48). One of these labs, the Purdue Innovation Lab for Food Processing, focuses on improving post-harvest practices to enhance nutrition and using



processing approaches to increase commercialization of nutritious foods from crops such as millet, sorghum, rice and corn (49). The Pan-Africa Bean Research Alliance (PABRA), part of the Alliance for Bioversity and CIAT, has also partnered with USAID Feed the Future Innovation Lab for Legume Systems Research to enhance bean processing efficiency in parts of Africa (50). Several food companies have also formed a collaboration, Partners in Food Solutions, to share industry knowledge, experience, and training with SMEs throughout Africa (51). The FAO in partnership with the International Agri-Food Network established a Women's SME Accelerator Program that matched women owners of SMEs in Sub-Saharan Africa with women agrifood leaders around the globe for business and innovation coaching (52).

While these innovation labs and private sector initiatives have had significant impact, there is also a need for more agro-industrial technology and training hubs in key locations in developing nations that can bring food science solutions specific to the needs of the region. Technology and engineering solutions must consider the local infrastructure and supply chain constraints while knowledge transfer and training must be relevant to the systems of the culture and gender sensitive.

Empowering youth as advocates for underutilized or biofortified crops

Not only is population growth accelerating in many developing countries, but young people make up a much greater portion of the population. Many of these young people end up moving to cities, or even other countries, to seek employment. However, providing these youth with education, training, and support can empower them to remain and make a difference in their communities and become innovators and advocates for the use of underutilized or biofortified crops.

“ These youth know their foods and their communities, but they need the playground to test their ideas and come up with brilliant products to improve lives, contribute to climate mitigation and promote health. ”

-Tawanda Muzhingi

Developing more and stronger food and nutrition programs in universities in developing countries can help provide much needed training and education for these youth. Beyond typical training on chemistry and technology, there should also be education on food culture, economics, and entrepreneurship/business. PPPs should also consider mechanisms that would enable young investigators at universities to participate. Most funding mechanisms require investigators to acquire matching funds from other private/public sector actors, which can be challenging for young investigators with limited network connections.

Understanding the needs of the consumer and changing demographics

With increasing urbanization in developed and developing countries, particularly among young people, there is growing demand for convenient and healthy options. In developed countries, many young urban residents are health focused and seek out new foods and ingredients with potential health benefits. These populations are likely to be the earliest adopters of foods made with nutrient-rich biofortified or underutilized crops.

Products must be designed to be culturally relevant and with the specific demographic in mind, or it is unlikely to be accepted. As discussed previously, many underutilized crops are considered the “food of the poor” so there is a tension between cultural relevance and the desire to avoid foods that remind individuals of their poverty. Foods should aim to meet the aspirational needs of the growing urban population. There is also a growing need for more convenience ready-to-eat foods, particularly in developing countries where many urban populations experience “time poverty” due to work schedules, long commutes and caring for family members.

Partnering with local influencers and role models, including chefs or culinary experts, to experiment with these crops in foods can accelerate their adoption and acceptance. As an example, The Chef’s Manifesto (part of the SDG2 Advocacy Hub) brings together more than 1,200 chefs from around the world with a goal of creating a more sustainable food system (53). Within their framework is the protection of biodiversity, investment in livelihoods, celebration of local foods, a focus on plant ingredients, and making food nutritious, affordable, and accessible. Underutilized and biofortified crops fit well into this framework and could serve as a launching point to expand the use of these crops. In fact, it was the introduction of quinoa by chefs in the early 2000s that have made it a more commonly consumed and well-known nutritious food today.

Food scientists can also partner with culinary experts, entrepreneurs, and farmers to better examine ways to integrate these crops into convenience foods for developed and developing regions. By way of illustration:

- Chef Pierre Thiam from Senegal began a start-up, Yolele Foods, with a goal to share Africa’s ingredients with the world through convenient, ready-to-eat foods and snacks made with fonio, an ancient and underutilized grain from West Africa (54).
- In Nigeria, Cato Foods is creating affordable food products that utilize biofortified vitamin A cassava to address micronutrient deficiencies and improve the livelihoods of the rural women and youth that grow the crops (55).
- In the US, Professor Torbert’s Orange Corn® offers grits, corn meal and corn flour made with vitamin A corn along with numerous recipes to incorporate these into foods (56).



Flavor and texture are also critical components of consumer acceptance and many biofortified and underutilized crops have stronger taste profiles that may impact liking. Many consumers have become more accustomed to the neutral taste and smooth texture offered by commodity crops, such as wheat in breads. Food scientists and technologists along with sensory and consumer scientists should work together to understand how to begin to slowly integrate these crops into mainstream foods. This could be done using blends of underutilized and commodity crops to allow consumers to slowly adjust to the taste. Additionally, introducing these foods at a younger age, as shown in the case study of Wholsum Foods and Sluorp Farm™, or in school meal programs, can help improve acceptance from childhood into adulthood.

Additional research, potentially through PPPs, could examine the taste, sensory and organoleptic properties of a wide variety of underutilized crops to determine how to best integrate these into convenience foods. Networks that bring together food and sensory scientists can also help build collaborations to develop consumer acceptable foods. One group already at work in this area is the African Network for Sensory Evaluation Research (ANSWER) (57). ANSWER brings together individuals from academia, food industry and research institutions to provide knowledge sharing, training, and capacity building on consumer science throughout Africa. While still a young organization, it provides a mechanism by which scientists can collaborate on research and best practices in consumer science (58).

Health messaging has also been shown to work in increasing acceptance and adoption of underconsumed nutritious foods. In Kenya, messaging about the health benefits of leafy vegetables had a meaningful impact on growth and consumption of these important but underutilized crops in Kenya (59). Additionally, many consumers in Africa and India are looking for foods that help with blood glucose management due to the growing prevalence of type 2 diabetes (60, 61). This creates an enabling environment for underutilized crops, particularly whole grains, legumes, and vegetables, that can be a rich source of dietary fiber that consumers associate with better blood glucose control. For foods made with biofortified crops, it is often not necessary to call out biofortification, but simply focus on the natural source of vitamins or minerals (18).



Collaborating with stakeholders across the food and public health system

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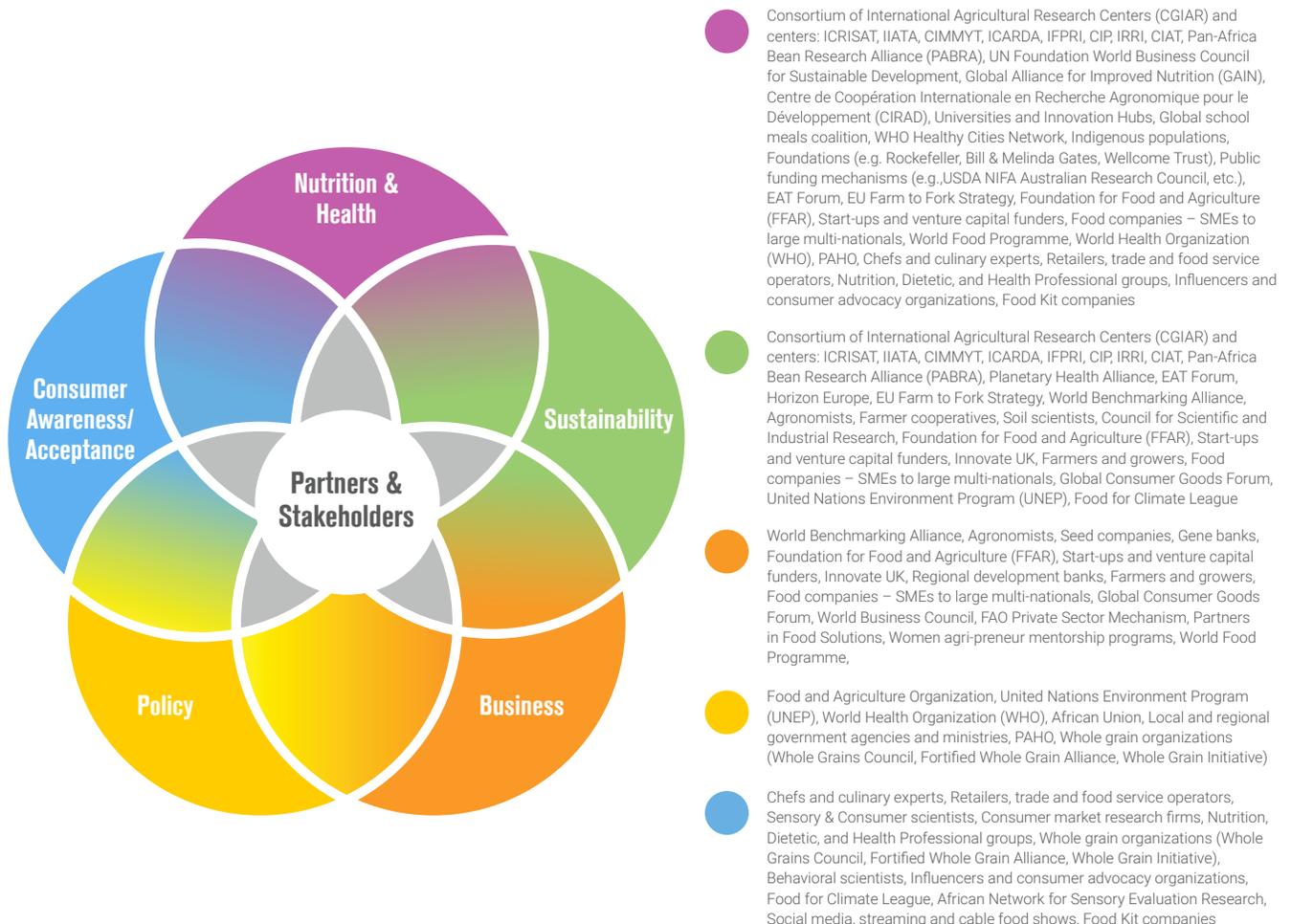
We need to involve multiple stakeholders across the food supply chain so that everyone in the food system is connected and benefits.

”

Kiruba Krishnaswamy

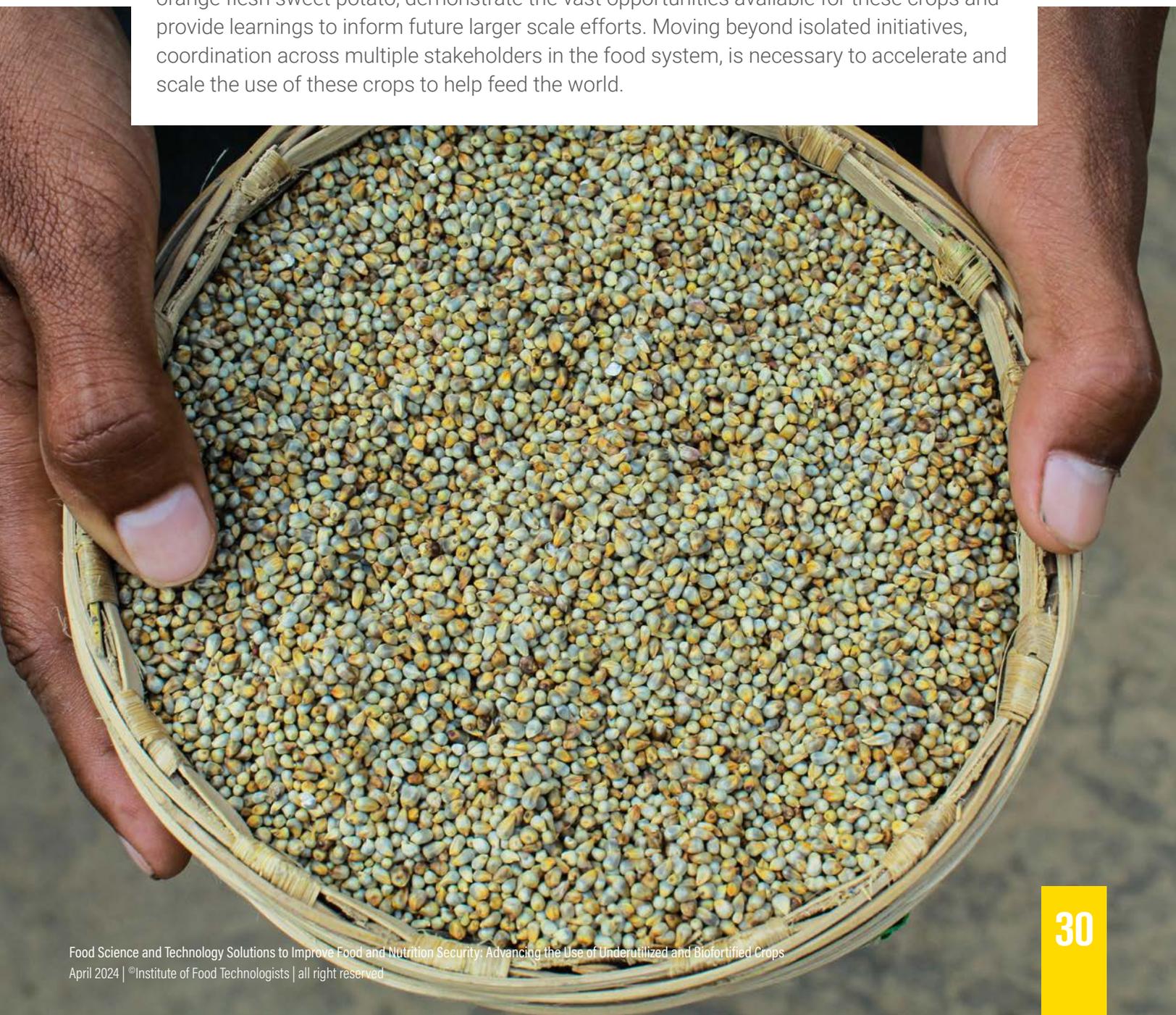
While various opportunities for collaboration have been discussed throughout this report, it must be stressed that collaborations with multiple stakeholders across the food system are necessary to achieve the enabling environment necessary to accelerate and scale the use of biofortified and underutilized crops within local regions and across the globe. In particular, advocacy with global policy makers to demonstrate the benefits that food science and technology can bring to improving nutrition security, farmer livelihoods and planetary health through the use of these crops is essential.

Figure 6: Examples of stakeholders and partners to engage for accelerating the adoption of underutilized and biofortified crops.



Conclusion

Underutilized and biofortified crops have considerable advantages for nutrition and health, economic prosperity, and environmental sustainability. Food science and technology is essential to help realize the full potential of these crops to address global food and nutrition security. As the global population continues to grow there is a sense of urgency to invest more into the research and development of these crops to advance their nutritional and planetary benefits. Numerous success stories with crops such as millets, zinc biofortified rice, and orange flesh sweet potato, demonstrate the vast opportunities available for these crops and provide learnings to inform future larger scale efforts. Moving beyond isolated initiatives, coordination across multiple stakeholders in the food system, is necessary to accelerate and scale the use of these crops to help feed the world.



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