Vision for Adapted Crops and Soils (VACS) Research in Action

Opportunity Crops for Africa

African Union | AgMIP | AOCC | Department of State United States of America | Food and Agriculture Organization of the United Nations | HAVOS.ai | The Rockefeller Foundation

Table of Contents

01 Authors

02 Foreword

03 Acknowledgements

04 Introduction

06 The VACS Approach: Driving Impactful Research and Development

08 Activities to Date

13 High-Level Findings

22 Evidence-Based Recommendations from Early VACS Research

28 How Can I Get Involved?

30 Bibliography

34 Annex

Authors

Title

Vision for Adapted Crops and Soils (VACS) Research in Action: Opportunity Crops for Africa

Coordinating Lead Authors

Emily Fredenberg (The Rockefeller Foundation),
Kevin Karl (AgMIP),
Simone Passarelli (USDoS),
Jaron Porciello (Havos.ai), and
Vieshnavi Rattehalli (USDoS).

Contributing Authors

Amy Auguston (The Rockefeller Foundation),
Gracian Chimwaza (ITOCA),
Fernanda Grande (FAO),
Bridget Holmes (FAO),
Natalie Kozlowski (AgMIP),
David Laborde (FAO),
Dilys MacCarthy (AgMIP),
Patricia Masikati (CIFOR-ICRAF),
Stepha McMullin (CIFOR-ICRAF),
Elena Mendez Leal (AgMIP),
Roberto Valdivia (AgMIP),
Allen Van Deynze (AOCC), and
Maarten van Zonneveld
(World Vegetable Center).

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Foreword

The world around us is changing at an alarming and accelerating rate. This past year—2023—was the warmest year on record by far; moreover, the ten warmest years recorded have all occurred in the last decade. Warming oceans have exacerbated weather patterns like El Niño, leading to extreme flooding in East Africa and droughts in Southern Africa. In their wake, these changing climate patterns wash away carbon-rich topsoil, diminish the bounty of our harvests, and threaten food and nutrition security worldwide.

The crops that sustain us took millions of years to evolve on our planet, with humans driving that evolution for thousands of years. This unprecedented pace of planetary change compels us to take a critical look at the food systems we have today and ask ourselves: how can we best prepare the most fundamental elements of agriculture—crops and soils—for what's to come? We are grateful for and certainly do not wish to detract from or reduce the efforts devoted to strengthening food security through actions not specifically related to VACS. We need both.

This is what motivated the U.S. State Department to reach out to our partners in the African Union (AU) and the Food and Agriculture Organization of the UN (FAO) to launch the Vision for Adapted Crops and Soils (VACS), with an initial focus on the African continent.

As part of VACS, we have partnered with and sought feedback from top technical experts across diverse fields, from nutrition to climate science to plant breeding. These experts have helped us investigate critical issues that will help us better prepare our food systems, from identifying which crops are most important for nutrition in Africa, to understanding how the productivity of those crops will be affected by a climate-changed world.

In this report, you will find a description of the process we've undertaken, including results of the crop-climate models and our vision for how those results might inform a path forward. Equally important, though, is what you won't find in this report. We will not claim to have included every crop that holds promise for nutrition or climate adaptation. We do not suggest that these models determine ultimate winners and losers. Rather, the goal of this analysis is to provide a starting point for research and policy discussions based on available evidence—because the planet will not wait for us to develop all the data we'd love to have or come up with a perfect solution.

I am extremely grateful to those who have been VACS partners from the beginning, including the AU, FAO, African Orphan Crops Consortium, AgMIP, Havos.ai, the CGIAR, and The Rockefeller Foundation. One of the defining characteristics of VACS is that it is not a project or a program; it is, as the name implies, a "vision" and now a movement. The key distinction is that a movement requires collective action and responsibility in order to advance. No one owns the concepts that VACS explores and promotes. No formal membership is required to take part in its work. I hope that anyone—whether they are a policymaker or a researcher, a corporate executive or a civil society leader, a public official, a private citizen, or a farmer—can take inspiration from VACS and apply its principles to their own work in their own sector. Together, individual actions make a big difference. It is only together that we can catalyze the changes we need in our global food system. Thank you for being a part of that movement!

With gratitude,

Dr. Cary Fowler
Special Envoy for Global Food Security, U.S. Department of State

Acknowledgements

The research team is especially grateful to the VACS Chairs, Lindiwe Sibanda, Consultative Group on International Agricultural Research (CGIAR); and Namukolo Covic, International Livestock Research Institute (ILRI) and President of the African Nutrition Society; and the VACS Steering Committee group for their leadership, including Godfrey Bahiigwa of the African Union Commission (AU); Maximo Torero, Food and Agriculture Organization of the United Nations (FAO); David Laborde, FAO; Lynnette Neufeld, FAO; Dr. Cary Fowler, U.S. Special Envoy for Food Security; and Robert Bertram, United States Agency for International Development (USAID).

The research team would like to thank Catherine Bertini and Roy Steiner, The Rockefeller Foundation; and Allen Van Deynze, African Orphan Crops Consortium (AOCC) for their important comments and guidance throughout. The conceptual approach to modeling work and adaptation indicators framework was led by Cynthia Rosenzweig of the Agricultural Model Intercomparison and Improvement Project (AgMIP). Climate-crop-economic modeling was executed under the leadership of Dilys MacCarthy, Alex Ruane and Roberto Valdivia of AgMIP. Analysis of crop facilitators and barriers was led by Jaron Porciello of Havos.ai, with support from Gracian Chimwaza of Information Training & Outreach Centre for Africa (ITOCA) and the Juno Evidence Alliance. Nutrition analysis was made possible under the leadership of Lynnette Neufeld, Bridget Holmes and Fernanda Grande of the FAO Food and Nutrition Division. Economic analysis was conducted by David Laborde of FAO.

The research team would also like to give thanks to over 80 technical experts from across Africa and other institutions, including gene bank experts, crop breeders, climate scientists, soil scientists, nutritionists, agricultural economists, and data scientists that participated in two technical convenings, the first in May 2023 at the headquarters of FAO in Rome and the second in November 2023 at The Rockefeller Foundation in New York City. These technical experts provided invaluable input to the research undertaken for this report. This report would not be possible without the broader AgMIP and Havos.ai research teams leading this effort.

About the Report: This report was produced to provide high-level insights for guiding VACS in its initial phases, with grant funding provided by The Rockefeller Foundation. Research developed for this report was led by the Agricultural Model Intercomparison and Improvement Project (AgMIP) and Havos.ai. **This Research Report was produced alongside the Opportunity Crop Profiles, which provide in-depth crop analysis for a non-exhaustive list of VACS crops. The Opportunity Crop Profiles can be found here.**

Introduction

Lablab

Sweet potato

African Eggplant

Yams

Cocoyam

Cowpea

Taro

Okra

Finger Millet

Teff

Sorghum

Mung bean/
green gram

Pigeon pea

Fonio

Bambara groundnut

Amaranth

Sesame

Groundnut

Grass pea

Pearl millet

More than 700 million people globally are undernourished, and child stunting and nutrient deficiencies are widespread in low- and middle-income countries (LMICs) around the world (FAO, 2023).

Global food demand is expected to increase by more than 50 percent by 2050, while climate change and other stressors such as soil degradation are expected to drive crop productivity down (Stewart et al, 2020; Jagermyer et al, 2021; van Dijk et al., 2021). Global overreliance on the international trade of a few staple crops, including maize, wheat, and rice, has led to systemic vulnerability, especially as extreme weather increasingly causes crop failures and reduced yields (Puma et al., 2015; Rosenzweig et al, 2014).

Indigenous and traditional food crops (sometimes referred to interchangeably as "neglected and underutilized crop species", "orphan crops", "lost crops", and "forgotten crops") can be well-adapted to local conditions, and many are nutritious (Chivenge et al, 2015). A portfolio of these crops is essential for regional food security and can provide communities with a source of local resilience in the face of changing weather patterns (Mabhaudi et al, 2019; van Zonneveld et al, 2023). They are particularly important in countries across Africa, many of which are particularly vulnerable to the twin impacts of climate change and land degradation processes such as soil erosion (Tadele et al, 2019; Pravalie et al, 2021).

VACS refers to these traditional and underutilized crops as "opportunity crops". Opportunity crops are culturally important and nutritionally complex, and have provided rural farmers, and often women, with important sources of nutrition and income, especially during lean seasons, when access to more commercialized crops can be limited (McMullin et al, 2019). Currently, these crops are not incentivized by agricultural policies, and their research and development, markets, value chains, and seed and propagation systems are often woefully underdeveloped (McMullin et al, 2021). Yet scaling up investments in opportunity crops has the potential to improve nutrition for families, enhance livelihoods, safeguard biodiversity, decrease reliance on food imports, reduce land degradation, and improve the efficiency of inputs like fertilizer and irrigation systems—which, in turn, can contribute towards lower greenhouse gas emissions and more sustainable global food security (Akinola et al., 2020; Kamenya et al., 2021; Vidigal et al., 2019).

The Vision for Adapted Crops and Soils (or "VACS") brings together dedicated communities and individuals from research, advocacy, and policy to shine a light on opportunities that opportunity crops provide to build more resilient and food systems. Scaling up production and access to more diverse, climate-resilient crop varieties that support good nutrition and better livelihoods is a goal shared across national, regional, and international communities. VACS has gained important visibility, including from the U.S. Secretary of State, Antony Blinken, which has galvanized further international support. This report outlines the guiding concepts of the VACS approach, provides an overview of the research conducted as part of VACS through crop-modeling and evidence synthesis approaches, and recommends areas of focus for the movement going forward as well as ways to engage in VACS.

The VACS Approach
Driving Impactful Research and Development

Reaching climate, nutrition, and food security targets requires increased and more effectively targeted investments. Achieving this relies heavily on the extent to which stakeholders at all levels are engaged in the research and development (R&D) process (Faure et al., 2020; Rosenzweig et al., 2021). The VACS approach recognizes and values that agricultural and dietary interventions should be context-specific, and that implementation is most successful when interventions are tailored to their social, political, and cultural environment, and integrated into existing farming systems.

To achieve its vision, VACS must be rooted in strong, robust, and transparent evidence. VACS has brought together a group of multidisciplinary technical experts to develop a research agenda for Africa. The results of the VACS research agenda will help to guide future investments by assessing multidisciplinary outcomes, resulting in a policy approach directly informed by evidence.

The first step in formulating this research agenda was to identify the African opportunity crops that were determined to be most critical and promising for making improvements to nutrition. Second, a subset of these crops was analyzed under climate scenarios projected to the year 2050 to assess their performance based on nutrition, biophysical, and plant breeding potential. This process has identified an initial list of promising opportunity crops, which can then be further assessed to determine the barriers that affect their adoption, uptake and scaling potential amongst farmers, consumers, and other actors across the value chain. Working with local, national and/or regional stakeholders to design targeted interventions that address such barriers, and leverage the unique strengths of these crops, will inform more impactful investments.

As VACS moves towards implementation, working with local organizations, local communities, the private sector, and civil society will be critical to driving impactful research. This includes collaborating with farmers through participatory plant breeding processes, engaging with consumers to identify desirable traits, and working with communities to understand socioeconomic and gender barriers and constraints to adoption and consumption. VACS will work across the entire value chain to build markets, processing capacity, and consumer products for new varieties—especially since many opportunity crops have limited existing commercial presence. Local engagement can help to drive an iterative process that engages local communities and drives impact and uptake of new varieties.

VACS promotes an integrated approach, emphasizing the interdependence of soil fertility and health with nutritious, climate-resilient agriculture, so that investments can be self-sustaining and increase returns year after year. Interventions will be organized around a cohesive, interdependent four-decision framework (see Figure 1) that recognizes the complexity of decision making involved in land use and agricultural management. This framework aims to provide context-relevant information for farmers, so that they can make informed decisions about:

where to plant crops,

which crops to plant,

which management practices to apply to their agricultural system, and

how to apply these management practices in localized contexts.

Increased awareness of options and access to knowledge will empower farmers, policymakers, agricultural extension workers, plant breeders and crop improvement specialists, and food suppliers to promote better nutrition now and for future generations.

Figure 1 The VACS Approach To Driving Impactful Research And Development

Co-developing innovative research agendas to drive impactful R&D investments

Co-develop research agenda
with multi-stakeholder engagements to drive impactful R&D investments

Identify
the traditional and indigenous crops and soil health practices most important for food security and nutrition

Assess
the projected impacts of climate change on soil health and on the production and availability of opportunity crops

To Drive Impact

Engaging Communities

Empower Communities

To Drive Impact

How to Apply to Diverse Crops
For each crop and conditions in a given year

What Crop Management Systems
For efficiency, productivity, soil health and sustainability

What to Plant
For productivity and nutrition

Where to Plant
For sustainable land use

Priority research areas

Activities to Date

VACS was launched in February 2023 in partnership with the African Union (AU), the Food and Agriculture Organization of the United Nations (FAO), and the Office of Global Food Security at the U.S. State Department, with an initial focus on the African continent.

VACS is a movement to champion nutritious, climate-resilient crops by focusing on agricultural fundamentals—seeds and soils. VACS began with a two-phase research initiative, starting with an identification of those opportunity crops with the greatest potential to improve nutrition in Africa. As part of that process, the FAO Food and Nutrition Division compiled nutrient composition data for an extensive list of underutilized crops in Africa (Phase 1). As part of Phase 2, AgMIP developed climate-crop models for a subset of these crops to project how their productivity will fare under different climate scenarios. Havos.ai used artificial intelligence large-language models (LLMS), combined with expert analysis from crop and plant scientists working throughout Africa, to analyze current and historical research on current barriers and potential facilitators for scaling up these crops for the future. The crops modeled included legumes, cereals, roots and tubers, nuts and oilseeds, and fruits and vegetables, as well as trees used for food, and ensured distribution of crops that are important throughout the five regions of Africa for their consumption, breeding potential, and contribution to improving soil quality. **The detailed results from the crop analysis—the Opportunity Crop Profiles—can be found here.**

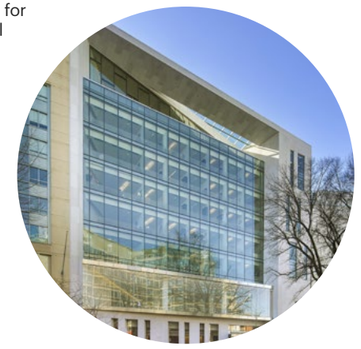
The Opportunity Crop Profiles build the evidence base for scaling investments in such crops in Africa, with the goal of providing additional production options for farmers and nutritious choices for consumers. This analysis is not meant to be exhaustive or exclusionary of other crops that hold potential; it is meant to serve as a starting point for research, investment, and policymaking. More refined analyses can be developed around a particular social, political, market, and cultural context and farming system.

AgMIP also implemented a Regional Integrated Assessment (Antle et al., 2015) for a case study in Navrongo, Ghana to model the impacts of incorporating a selected opportunity crop into current production systems. The climate-crop-economics modeling approach assessed the potential adoption of cowpea (Vigna unquiculata) and the associated socio-economic impacts (e.g., changes in farm income and food insecurity, etc.) under the current and future climate. This was co-led by Roberto Valdivia (Oregon State University) and Dilys MacCarthy (University of Ghana).

In addition to the evidence synthesis work in the opportunity crops profiles, Havos.ai and the Shamba Centre for Food and Climate led three focus group workshops with African public and private sector actors focused on consumer demand and preferences for these crops. A case study on fonio and other millets that combined species distribution modeling and qualitative research was coordinated by Havos.ai and co-led by Michel Ghanem, CIRAD, and Greg Sixt, MIT FACT Alliance.

Figure 2 **Timeline of Major VACS Activities to date**

February 1st, 2023
Launch of VACS at Center for Strategic and International Studies (Washington DC)



June 22, 2023
Focus group workshop:
How do private and public sector organizations view opportunity crops?

July 19, 2023
Focus group workshop:
What are the major policy and regulatory barriers facing opportunity crops?

October 10th, 2023
Focus group workshop:
Case study on market demand for fonio

November 28-29th, 2023
Phase 2 Technical Convening
hosted by The Rockefeller Foundation (New York City)

March 14, 2024
Summary Report and Opportunity Crop Profiles launch

February – May 2023

- Compilation of initial VACS crop list (~150 Crops) by U.S. DoS, utilizing resources from AOCC and other African crops experts
- Initial nutrient composition research by FAO Nutrition Division
- AI-assisted mapping of 500,000 articles for workshop by Havos.ai

June – November 2023

- Group deliberation with African crop experts to identify ~60 most promising crops
- Group deliberation and voting with African crop experts to prioritize non-exhaustive list for climate-crop modeling
- AgMIP climate-crop modeling for 24 crops
- AgMIP Regional Integrated Assessment in Navrongo, Ghana
- Havos.ai evidence synthesis network building and research

May 18-19th, 2023
Phase 1 Technical Convening
at FAO (Rome)

June 26th, 2023
Hybrid Convening
at AgMIP9 Global Workshop
(New York City)

September 20, 2023
High-level advocacy event
on the sidelines of UNGA, with participation from U.S. Secretary of State.
(New York City)

October 10-12th, 2023
VACS evidence synthesis research network launched
with 16 African scientists
(Pretoria)

December 1st, 2023
Secretary of State announces financial commitments from US
for VACS at COP28 (Dubai)

VACS builds upon the substantial work that has already been conducted on opportunity crops. This includes efforts to identify, prioritize, promote, and evaluate these crops, including the development of four lists of opportunity crops that contributed to the Phase 1 review. The original compilation included all 101 crops determined by a complex, multi-stakeholder survey conducted by the AOCC and endorsed by the AU. We also considered crops modeled by van Zonneveld et al. in their 2023 publication and crops compiled in a review by van Zonneveld et al. (2020), and crops reviewed by Akinola et al. (2020). **The process of selecting an indicative list of 60 crops from the initial longer list during Phase 1 is outlined in the VACS Phase 1 Workshop Report here.**

Although there are numerous opportunity crops that could have been included and could be candidates for future work, this list serves as a starting point based on a collaborative, multistakeholder process to determine a key set of nutritious African opportunity crops. The compilation of nutrition data was led by Bridget Holmes and Fernanda Grande at the FAO Food and Nutrition Division using available food composition tables. Climate-crop modeling was led by co-led by Dilys MacCarthy (University of Ghana), Jose Guarin (Columbia University) and Meijian Yang (Columbia University) through AgMIP. The analysis of crop barriers and use facilitators was led by Jaron Porciello (Havos.ai) and Gracian Chimwaza (ITOCA) as part of the Juno Evidence Alliance.

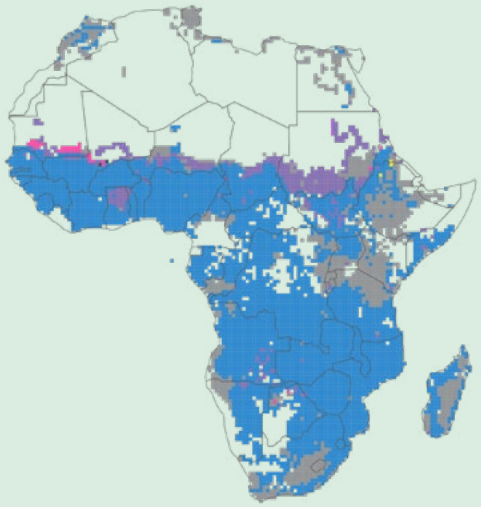
All this research was further analyzed and deliberated through two technical convenings, the first in May 2023 at the headquarters of FAO in Rome and the second in November 2023 at The Rockefeller Foundation in New York City. These technical convenings engaged experts from diverse organizations and disciplines, including gene bank experts, agronomists, plant breeders, climate scientists, soil scientists, nutrition experts, and agricultural economists.

Although there are numerous opportunity crops that could have been included and could be candidates for future work, this list serves as a starting point based on a collaborative, multistakeholder process to determine a key set of nutritious African opportunity crops.

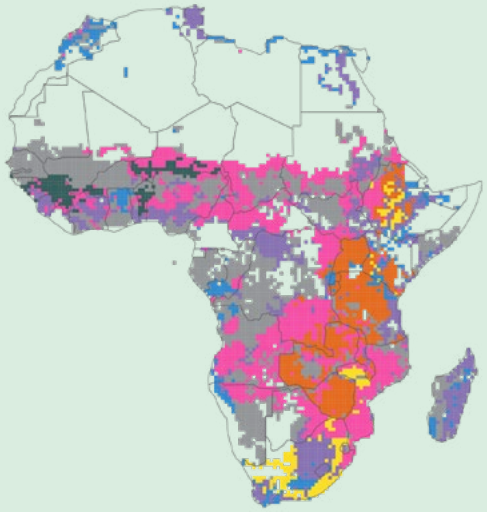
Prof. Lindiwe Majele Sibanda (CGIAR System Board Chair) addressing the VACS session at The Rockefeller Foundation Headquarters, USA

Figure 3

Largest Decrease in Relative Yield Amongst Cereals
High Emissions scenario, 2050s



Largest Increase in Relative Yield Amongst Cereals
High Emissions scenario, 2050s



Legumes

None	Maize
Tef	Finger millet
Fonio	Sorghum
Pearl Millet	

Largest projected relative decreases and increases in crop productivity among cereals modeled by AgMIP, high emissions scenario (SSP 3-7.0), 2050s (2035-2064 average) relative to historic (1990-2019 average)

Research Findings

Research presented in this report points to five major high-level findings that can help guide implementation for stakeholders across the VACS movement. We find that investing in opportunity crops and healthier soils can:

1. Create more climate-resilient local, national, and regional agricultural systems;
2. Encourage increased consumption of nutritious foods that can contribute to healthy diets;
3. Distribute economic resources more equitably to smallholder farmers;
4. Increase biodiversity and create more food-secure and resilient agricultural systems; and
5. Create opportunities for governments and institutions to broaden their food system agendas.

Finding 1

Opportunity crops can create more climate-resilient local, national, and regional agricultural systems.

AgMIP developed climate-crop models for 24 crops, 20 opportunity crops and 4 comparator crops to project how their productivity may fare under a range of emissions scenarios. The selection of which crops to model was guided by a multi-stage consultative process with African crop experts listed in the Annex of this report, and based on a series of criteria that are articulated in the VACS Phase 1 Workshop Report.

Figure 3 displays the combined yield change projections for all the cereals that AgMIP has modeled to date. Crop productivity was simulated only in areas where the crops are currently grown. Preliminary results indicate that maize is projected to decrease in productivity in most areas of Africa and is projected to see the largest relative yield losses of all cereals modeled. A variety of cereal crops are projected to be significantly more climate-resilient than maize across most areas of the continent. Pearl millet projects to be a strong option in many regions across the continent, including in Sahelian zones, with fonio being particualrly resilient in West Africa, finger millet in East Afirica, and sorghum showing potential in wide range of geographies. **Research results for all opportunity crops, including combined results for each crop group, can be found in the Opportunity Crop Profiles here.**

For legumes, grass pea is projected to be particularly resilient in parts of Eastern and Northern Africa, while cowpea is poised to be a resilient option in many areas of West and Central Africa (though less so deeper into the Sahel), which is further confirmed by the integrated assessment case study in Navrongo, Ghana on cowpea. Bambara groundnut and pigeon pea display high resilience in many areas across the continent, but their productivity projections are highly dependent on local factors. For roots and tubers, cassava is poised to perform well across the continent in a high-emissions scenario, with taro proving to be a promising option in Central Africa, and sweet potato projecting to be a climate-resilient option in many parts of Eastern Africa. For oilseeds, both groundnut and sesame appear to be resilient under high emissions climate change scenarios in most regions across the continent. For vegetables, okra shows promise to be climate-resilient, particularly in West Africa.

A variety of cereal crops are projected to be significantly more climate-resilient than maize across most areas of the continent.

Finding 2

Increased availability and access to nutritious opportunity crops can contribute to improving diets

Underutilized, uncultivated, wild, indigenous, traditional or neglected crops— those that have been overlooked by research, extension services and policy makers—are often highly nutritious. Some lesser-known cultivars or wild varieties of crops such as sweet potato, taro, cassava and rice may even be superior in terms of micronutrient composition compared to more extensively utilized cultivars. The difference in nutrient composition between neglected and underutilized crops and their more dominant staple varieties can vary widely. In some cases, the intake of one variety versus another can be the difference between adequate or inadequate consumption of a nutrient.

The Juno Evidence Alliance undertook an evidence synthesis of existing, high-quality literature to explore how opportunity crops—selected through a multi-stage consultative process described above—contribute to a range of interventions and outcomes relevant for both nutrition and climate adaptation. Using a combination of artificial intelligence and traditional evidence synthesis approaches, 14 expert scientists working across Africa reviewed thousands of research papers and identified research containing high-quality empirical or experimental results.

There is some evidence (Figure 4) to acknowledge how opportunity crops contribute to some interventions that may have an impact on diets. For example, crops important in West Africa, such as orange-fleshed sweet potato and cowpea, have been researched to understand consumer demand for preferences including taste, color, and texture (Gewa et al., 2019; Hotz et al., 2012; Low et al., 2007, Chanadang et al., 2018, McMillan et al., 2022). In addition, some of the opportunity crops, including sorghum, finger millet, groundnut, and Bambara groundnut, are currently added to infant porridges, stews, soups, and other commonly prepared foods, as part of complementary feeding or school feeding programs that in some cases assess impacts on nutritional growth outcomes (Anitha et al., 2022; Banda et al., 2021; Bouis & Saltzman, 2017; Delimont et al., 2017; Kpaka et al., 2022; Kubuga et al., 2023).

However, the evidence on the role of opportunity crops to support nutrition is limited. So, too, is the underlying data supporting the nutrient composition of opportunity crops, which is often unknown. A few national food composition tables (FCT) have successfully incorporated data on underutilized foods or of different varieties of the same crop in their publications. For example, the Indian FCT (2017) lists 21 different brinjal varieties (Solanum melongena) (Longvah, Thingnganing, et al., 2017), and the West African FCT (2019) provides data for minor crop species such as fonio, sorghum and pearl millet (Vincent A, Grande F, Compaoré E, Amponsah Annor G, Addy PA.et al. 2020). A key aspect to reinforce the importance of such species is the knowledge of their nutrient composition.

Using a combination of artificial intelligence and traditional evidence synthesis approaches, 14 expert scientists working across Africa reviewed thousands of research papers and identified research containing high-quality empirical or experimental results.

Figure 4

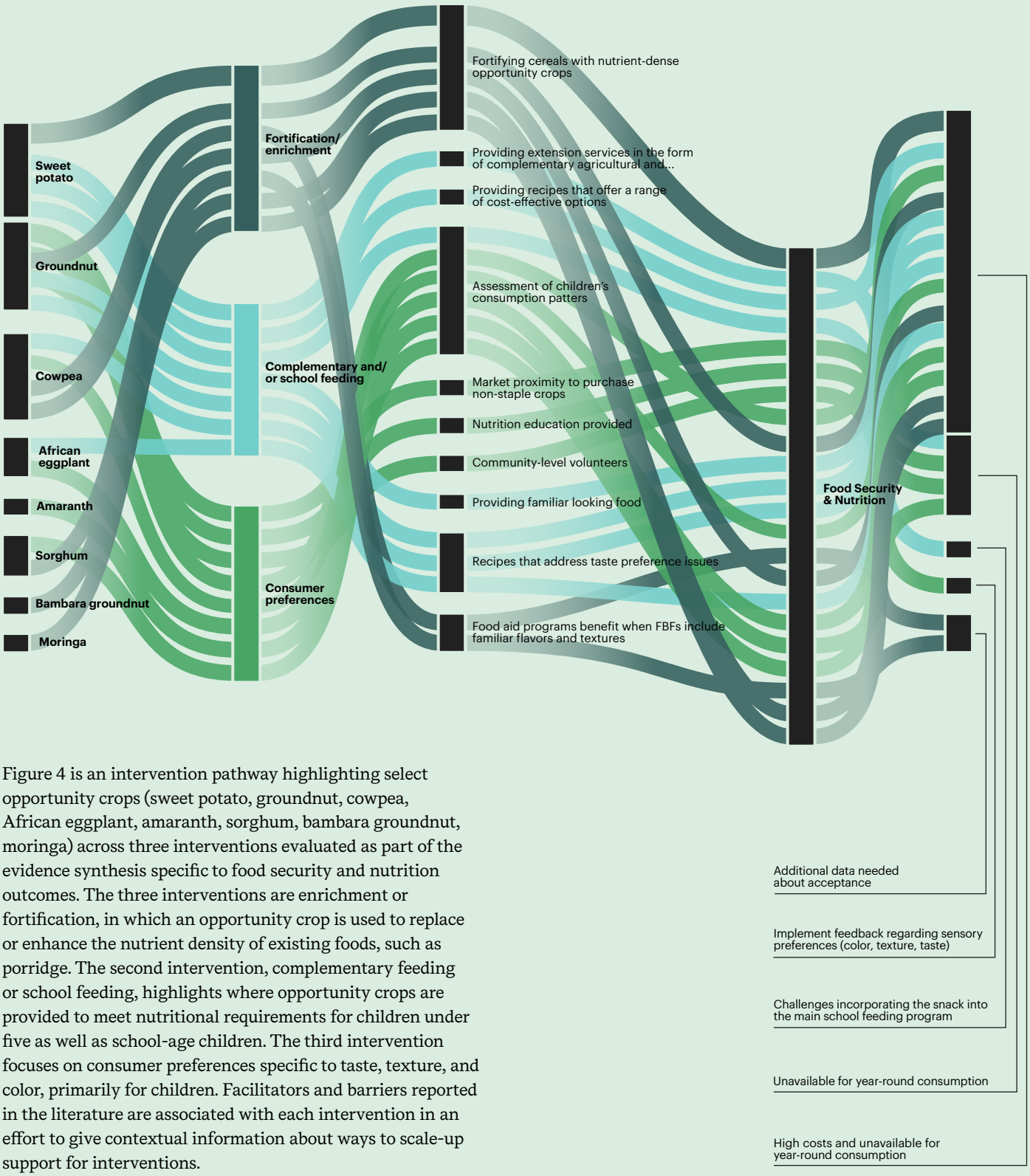


Figure 4 is an intervention pathway highlighting select opportunity crops (sweet potato, groundnut, cowpea, African eggplant, amaranth, sorghum, bambara groundnut, moringa) across three interventions evaluated as part of the evidence synthesis specific to food security and nutrition outcomes. The three interventions are enrichment or fortification, in which an opportunity crop is used to replace or enhance the nutrient density of existing foods, such as porridge. The second intervention, complementary feeding or school feeding, highlights where opportunity crops are provided to meet nutritional requirements for children under five as well as school-age children. The third intervention focuses on consumer preferences specific to taste, texture, and color, primarily for children. Facilitators and barriers reported in the literature are associated with each intervention in an effort to give contextual information about ways to scale-up support for interventions.

Finding 3

Investing in opportunity crop development can distribute economic resources more equitably to smallholder farmers

Smallholder farms represent most of the farms across Africa, and many of these farms already grow opportunity crops for home consumption. Plant breeding investment has historically focused on the most economically important cash crops. As Figure 5 shows, a diverse range of opportunity crops have been historically underinvested in relative to benchmark crops, which are often grown on higher quality land, and with more inputs than opportunity crops. By rerouting investment into a range of opportunity crops that are typically grown by smallholder farmers, VACS presents an opportunity to enable less-resourced communities— many of which are already vulnerable to climate change— to benefit more directly from agricultural development investments and reduce the large productivity gaps that have accumulated over the past decades.

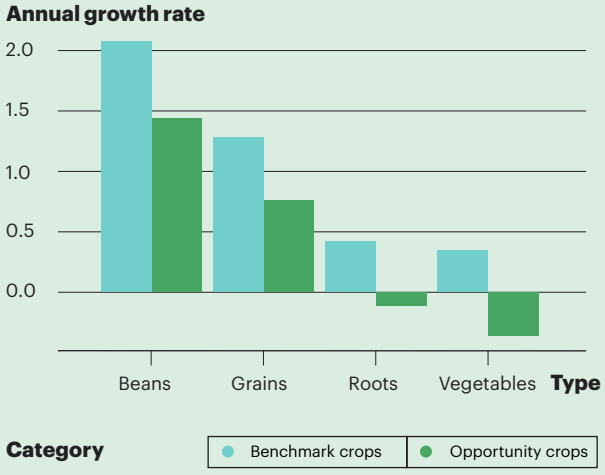
Finding 4

Adopting a portfolio approach to the introduction of opportunity crops can increase biodiversity and create more resilient and food-secure agricultural systems

Diversifying agricultural production systems is important for addressing seasonal variations in local food availability, improving nutrition, and supporting local biodiversity. Several tools, such as the 'food tree and crop portfolio' approach, are available to help select suitable species for diversification of local production systems across Africa. This approach advocates cultivating a variety of ecologically suitable trees and complementary annual crop species with different harvest seasons in one location, ensuring year-round food sources and a stable supply of critical micronutrients.

Emphasizing a portfolio approach to integrate opportunity crops into farming systems offers a wider range of options that can supplement staple-based food production and deliver healthier diets in Africa under climate change. As Figure 6 demonstrates—using a non-exhaustive list of potential crops—tree foods and leafy vegetables can provide key sources of vital micronutrients, such as vitamins A and C, iron, and folate, year-round. These are considered significant in dietary diversification strategies due to their often-scarce presence in staple-based production systems.

Figure 5 **Annual growth rate of yields, Last 50 years**



Annual growth rate of yields of Opportunity Crops vs. Benchmark Crops in Africa over the last 50 years.

Source: Author's computation based on FAOSTAT

Figure 6 **A site-specific food tree and crop portfolio for Chibale in Central Province in Zambia**

Common Name	*	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Vit A	Vit C	Iron	Folate
Mango	E	■											■	○	○		
Avocado	E	■	■	■									■				
Guava	E	■	■	■	■										○	●	
Orange	E			■	■	■	■	■							○		
Lemon	E						■	■							○		
Chocolate berry	N							■	■	■				●			●
Baobab	N								■	■					○	○	
Mobola plum	N								■	■				○	●	●	○
Wild pear	N								■	■				●	○	○	●
Mfungo	N								■	■				●	●	○	●
Wild Loquat	N									■	■	■	■		○		○
Monkey Orange	N									■	■	■	■				●
Wild Granadilla	N										■	■		○	○		●
Leafy Vegetables																	
Bean leaves		■										■	■	●	●	●	●
Sweet-potato leaves			■	■	■									○		○	○
Pumpkin leaves	N	■	■	■	■	■	■	■	■	■	■	■	■	○		○	
Staples																	
Millet	N					■	■									○	
Maize							■	■									

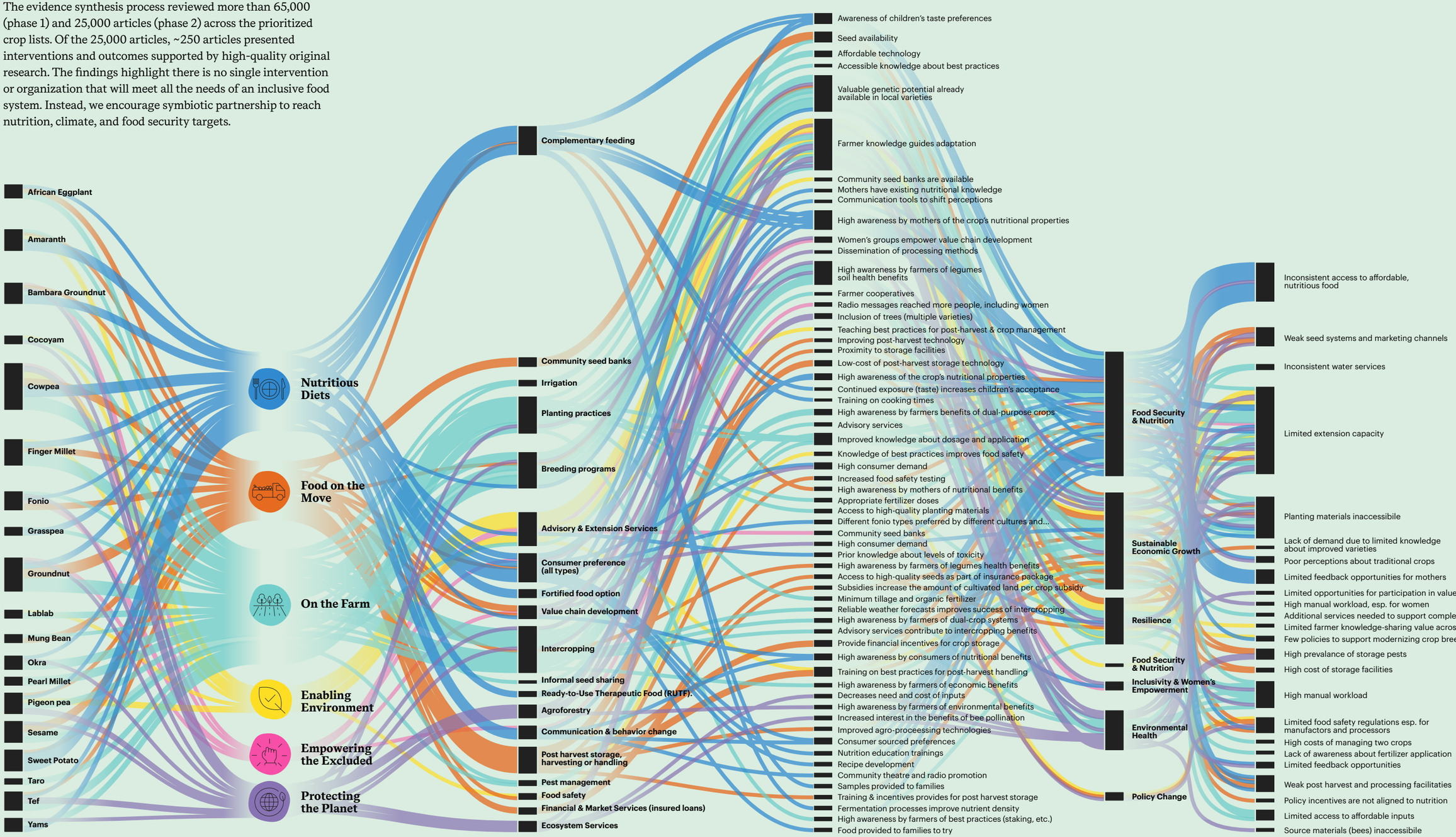
Customized crop portfolios promote diversification to provide micronutrients in staple-based systems, with native and exotic species filling food harvest gaps especially during lean season, and prioritize micronutrients that are considered significant in dietary diversification strategies due to their often-scarce presence in staple-based production systems.

● No quality data available	○ High source
○ Source	Present, but low
○ No source	*Exotic (e), native (n)
■ Harvest window	

Figure 7

Crop	Pathway	Interventions	Key Facilitators	Outcomes	Barriers to Implementation

The evidence synthesis process reviewed more than 65,000 (phase 1) and 25,000 articles (phase 2) across the prioritized crop lists. Of the 25,000 articles, ~250 articles presented interventions and outcomes supported by high-quality original research. The findings highlight there is no single intervention or organization that will meet all the needs of an inclusive food system. Instead, we encourage symbiotic partnership to reach nutrition, climate, and food security targets.



Finding 5

The VACS movement can create opportunities for institutions to broaden their food systems agendas

There is already an active and thriving ecosystem of programs, research, and value chain development that supports many opportunity crops (Figure 7). And while there is more high-quality evidence and knowledge on certain interventions and outcomes than others, the breadth and depth of work underpinning opportunity crops highlights a crucial message. There is no single approach, organization, or intervention that will meet all the needs of an inclusive food system. We need to work together to reach nutrition, climate, and food security targets.

There are some interventions that are critical to scale up opportunity crops (McMullin et al., 2021). For example, better decision making across agriculture requires significant investments in better evidence and data across the food system (Lipper et al, 2020). Farmers and small-scale producers adjust their behavior and investment decisions in response to accurate data. The use of and reliance on advisory and extension services (digital or otherwise) by farmers looking to adopt better management practices is high and contributes to a range of food systems outcomes (Jerop et al., 2018, Ekepu et al., 2017). Although governments collectively employ many extension workers in low- and middle-income countries, the ratio of farmers to extension workers frequently exceeds 1000 to 1 in many countries (Davis & Franzel, 2019). Extension workers will, in turn, require upskilling to support the specific questions of farmers on best practices to support opportunity crops. As highlighted in Figure 4, some interventions such as complementary and school feeding are already using a range of opportunity crops (Hassanally et al., 2020; Wineman et al., 2022, Chagomoka et al., 2015). Other interventions, including agroforestry, intercropping, and post-harvest technologies, are increasingly being called up and studied to meet economic, environmental, and social inclusion goals (Bado et al., 2021, Giné & Yang, 2007, Fahmi 2018). One notable weakness in the research is a lack of outcomes on women's empowerment and inclusivity; very few scientists are integrating these outcomes and describing the findings within research and technical papers on opportunity crops.

There is no single approach, organization, or intervention that will meet all the needs of an inclusive food system. We need to work together to reach nutrition, climate, and food security targets.

Evidence-based Recommendations from Early VACS Research

Data on opportunity crops are lacking. Investing in adequate data and information systems for these crops will be required to scale up investments, guide decision making, and track performance in future years. Nevertheless, research findings to date support ten key recommendations to create the enabling environment for the VACS movement. While this list is not meant to be exhaustive, these include broad areas of interventions that should be prioritized and adapted accordingly to each unique context.

Implementing and maintaining effective soil health management practices requires a multifaceted approach. Incorporating organic materials such as compost and crop residues can significantly improve soil fertility and structure. Additionally, adopting conservation agriculture principles, which include minimal soil disturbance, maintaining permanent soil cover, and implementing diversified crop rotations, is crucial for sustainable soil health. These practices are essential for maintaining soil biodiversity, improving water retention, and reducing erosion. Sensitivity tests conducted throughout the climate-crop modeling process indicate that crop productivity is highly sensitive to changes in soil parameters such as the water-holding capacity of soil, which is critical for long-term agricultural viability in arid and semi-arid regions.

Investing in robust seed systems for opportunity crops in Africa involves a multi-pronged approach, including developing public-private partnerships that stabilize and expand early generation seed production programs, improving platforms for plant genetic resource (PGR) distribution across the continent, and working with farmers to ensure efforts are geared towards their unique needs for distribution and adoption. Data in this report show that opportunity crops consistently possess fewer plant genetic resource samples in conservation systems compared to major staples, highlighting the need for a concerted effort in seed system development, including enhancing farmer-to-farmer seed exchange mechanisms and engaging small- and medium-sized seed companies.

Developing climate-resilient crops through plant breeding is a complex task that involves identifying key genetic traits for tolerance to extreme and fluctuating weather and emerging pests and diseases. This requires collaboration among geneticists, agronomists, crop modelers, plant breeders, seed companies, and farmers to ensure that new varieties are resilient, high-yielding, and suitable for local needs. Breeding for drought- and heat- tolerance should involve trait identification. Moreover, consumers must be engaged in the process of varietal selection to ensure that crops meet standards for cooking, taste, nutrition, and other desirable traits. The urgency for such programs is underscored by the yield projections in this report, which show the increasing vulnerability of many crops, with their current genetics, to climate change. It is crucial that crop improvement efforts do not neglect nutritional content in their effort to develop higher yielding varieties..

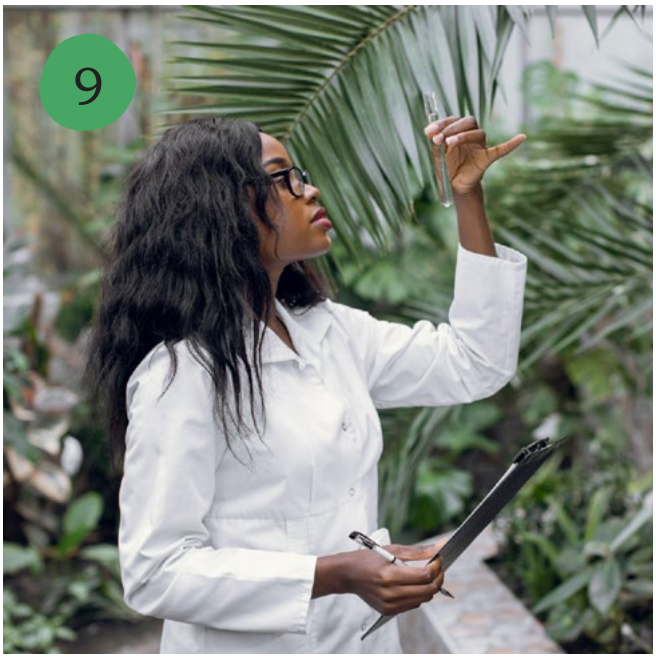
Crop diversification is a vital strategy for enhancing climate resilience in agriculture, involving the introduction of a variety of crops that can withstand different climatic stresses and provide year-round nutrition. This approach reduces dependency on a single crop type, thereby mitigating risks associated with climate variability and extreme weather events. Analysis in this report shows that there are a wide range of opportunity crops that are poised to yield well in a variety of localized contexts, and which could be used to supplement and bolster farming—systems that rely heavily on only a few crops.

Investing in opportunity crops is a pathway towards more equitable resource distribution for smallholder farmers, often women, who are already the primary growers and consumers of these crops. Economic data analysis from this research effort indicates that investments in opportunity crops rather than solely in major staples can lead to more stable and sustainable livelihoods for smallholder farmers, lowering poverty rates, empowering women, and improving food and nutrition security.

Scaling up market opportunities and value chains requires that nutritious crops are readily available throughout the year, affordable, and available for use and purchase by consumers, processors, and other market-actors. School and complementary feeding programs and nutrition education can be effective pathways to mainstream opportunity crops as part of everyday life (Figure 4). Strengthening these market opportunities to facilitate access for farmers, community seed banks, market processors, and retailers increases resiliency in local food systems while simultaneously supporting economic growth, nutrition, and food security for communities.

Opportunity crops are already a vibrant part of many cultures and communities and are readily accepted by millions of people as part of a healthy, sustainable diet. Scaling up these crops to make them available for purchase requires significant investments and advancements in post-harvest processing technologies and demand creation to ensure safe, affordable, and in-demand foods (Figure 5).

Advisory and extension services are the bedrock for farmers and small-scale producers to adjust their management and investment decisions in response to accurate data. The use and reliance of advisory and extension services by farmers is widespread and nearly ubiquitous; as Havos.ai research shows in the Opportunity Crop Profiles Report, the most common barrier to implementing any interventions for opportunity crops is extension and advisory services. Conversely, these services act as a primary facilitator for farmer adoption of new crops. And while these services are helpful for all farmers and market actors, the evidence shows that advisory and extension services are especially effective for women when provided in collaboration with women's groups or cooperatives.



Consumer preference data and farmers' knowledge on best practices are essential for crop breeders, plant scientists, and others in the research and development community. Currently, public sector participatory research methods to elicit farmer and consumer data, as well as feedback channels on adoption rates of new crops, are underdeveloped. Addressing this through improved transparency, data systems, and coordination can produce more inclusive, demand-driven varietal design and ensures that the preferences and opinions of women farmers and other traditionally marginalized communities are included.

Strengthened policy and regulatory environments are essential to scale up opportunity crops. Currently, these crops are largely missing from global, continental, and national agricultural policies. This excludes them from investment and promotion initiatives, subsidy programs, food safety regulation, regulation of plant genetic resources, and agriculture extension services. Improving national-level policies could potentially provide greater diversity and availability of micronutrients to populations and enhance overall diet quality. Creating a robust enabling environment will require renewed efforts of coordination and advocacy by local and regional partners, with commensurate support by the international community.

[Developing climate-resilient crops] requires collaboration among geneticists, agronomists, crop modelers, plant breeders, seed companies, and farmers to ensure that new varieties are resilient, high-yielding, and suitable for local needs.

How Can I Get Involved?

There are several ways for interested organizations and institutions to become involved with VACS. VACS is a set of ideas and principles adopted on a voluntary basis by like-minded organizations. All organizations who take VACS principles and adopt them into their work are part of the VACS movement.

Multilateral institutions such as the CGIAR, FAO, and the International Fund for Agricultural Development (IFAD) have set up channels to receive contributions from country donors and private sector partners to fund activities and interventions to advance VACS objectives. Host organizations will manage these funds, guided by the VACS approach and research outputs of this report and with advice from technical experts, country governments, donors, civil society, implementing partners, and VACS leaders (the African Union, FAO, and the U.S. Government).

In addition to bilateral and multilateral donor-funded programming that aligns with VACS, the VACS movement also offers the VACS Champions Program and the VACS Community of Practice as additional ways to get involved. The VACS Champions Program recognizes private sector and other non-governmental organizations for undertaking projects committed to developing climate-adapted nutritious crop varieties and building healthy, fertile soils. Organizations identified as VACS Champions will be publicly recognized and will be free to refer to themselves publicly as such. VACS Champions is a self-certification program. For contributing and implementing organization(s) to be considered for designation as a VACS Champion, they must submit a pledge identifying their project and indicating how the project advances one or more of VACS' key objectives. These key objectives include: accelerating plant breeding efforts and research for a targeted set of nutritious, opportunity food crops to deliver improved seeds to smallholder farmers; reversing trends toward land degradation and nutrient deficiencies in soils by increasing access to knowledge and information at the farm and field level; and advancing tailored demand-side solutions to support market commercialization and scaled consumer adoption in the regions of focus. For more information about how to become a VACS Champion, please reach out to: Globalfoodsecurity@state.gov.

The VACS Community of Practice aims to bring together technical partners in strategic planning and implementation discussions for VACS through a series of virtual discussions on various topics. It will provide a discussion forum centered on themes and projects related to VACS priorities. The Community of Practice is open to all who are interested; please reach out to Globalfoodsecurity@state.gov if you would like to join the mailing list. Please check the website of the Office of Global Food Security at the State Department and the LinkedIn page for Special Envoy for Global Food Security Dr. Cary Fowler for updates and more information on VACS. You can also reach out to Globalfoodsecurity@state.gov with any questions.

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List of Works Cited

Akinola, R., Pereira, L. M., Mabhaudhi, T., De Bruin, F. M., & Rusch, L. (2020). A review of indigenous food crops in Africa and the implications for more sustainable and healthy food systems. Sustainability, 12(8), 3493.

Anitha, S., Givens, D. I., Subramaniam, K., Upadhyay, S., Kane-Potaka, J., Vogtschmidt, Y. D., Botha, R., Tsusaka, T. W., Nedumaran, S., Rajkumar, H., Rajendran, A., Parasannanavar, D. J., Vetriventhan, M., & Bhandari, R. K. (2022). Can Feeding a Millet-Based Diet Improve the Growth of Children?—A Systematic Review and Meta-Analysis. Nutrients, 14(1). Scopus. https://doi.org/10.3390/nu14010225

Antle, John, Roberto O. Valdivia, Ken Boote, Jerry Hatfield, Sander Janssen, Jim Jones, Cheryl Porter, Cynthia Rosenzweig, Alex Ruane, and Peter Thorburn. (2015). AgMIP's Trans-disciplinary Approach to Regional Integrated Assessment of Climate Impact, Vulnerability and Adaptation of Agricultural Systems. In Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP). C. Rosenzweig, and D. Hillel, Eds., ICP Series on Climate Change Impacts, Adaptation, and Mitigation Vol. 3. Imperial College Press, doi:10.1142/9781783265640_0002.

Bado, B. V., Whitbread, A., & Sanoussi Manzo, M. L. (2021). Improving agricultural productivity using agroforestry systems: Performance of millet, cowpea, and ziziphus-based cropping systems in West Africa Sahel. Agriculture, Ecosystems & Environment, 305, 107175. https://doi.org/10.1016/j.agee.2020.107175

Banda, T., Chawanda, K., Tsuchida, W., & Kathumba, S. (2021). Report of a Pilot Program Using a Milk-Free Ready-to-Use Therapeutic Food Made From Soya, Maize, and Sorghum to Treat Severe Acute Malnutrition. Food and Nutrition Bulletin, 42(1), 91–103. Scopus. https://doi.org/10.1177/0379572120968703

Bouis, H. E., & Saltzman, A. (2017). Improving nutrition through biofortification: A review of evidence from HarvestPlus, 2003 through 2016. Global Food Security, 12, 49–58. Scopus. https://doi.org/10.1016/j.gfs.2017.01.009

Burlingame B, Charrondiere R, Mouille B. (2009). Food composition is fundamental to the cross-cutting initiative on biodiversity for food and nutrition. Journal of Food Composition and Analysis 22 (2009) 361–365.

Chagomoka, T., Drescher, A., Glaser, R., Marschner, B., Schlesinger, J., & Nyandoro, G. (2015). Vegetable production, consumption and its contribution to diets along the urban-rural continuum in Northern Ghana. African Journal of Food, Agriculture, Nutrition and Development, 15(4), Article 4. https://doi.org/10.18697/ajfand.71.15530

Chanadang, S., Chambers, E. I., Kayanda, R., Alavi, S., & Msuya, W. (2018). Novel Fortified Blended Foods: Preference Testing with Infants and Young Children in Tanzania and Descriptive Sensory Analysis. Journal of Food Science, 83(9), 2343–2350. https://doi.org/10.1111/1750-3841.14287

Chivenge P, Mabhaudhi T, Modi AT, Mafongoya P. The Potential Role of Neglected and Underutilised Crop Species as Future Crops under Water Scarce Conditions in Sub-Saharan Africa. (2015). International Journal of Environmental Research and Public Health. 12(6):5685-5711. https://doi.org/10.3390/ijerph120605685

Delimont, N. M., Chanadang, S., Joseph, M. V., Rockler, B. E., Guo, Q., Regier, G. K., Mulford, M. R., Kayanda, R., Range, M., Mziray, Z., Jonas, A., Mugyabuso, J., Msuya, W., Lilja, N. K., Procter, S. B., Chambers, E., Alavi, S., & Lindshield, B. L. (2017). The MFFAPP Tanzania Efficacy Study Protocol: Newly Formulated, Extruded, Fortified Blended Foods for Food Aid. Current Developments in Nutrition, 1(5), e000315. https://doi.org/10.3945/cdn.116.000315

Ekepu, D., Tirivanhu, P., & Nampala, P. (2017). Assessing farmer involvement in collective action for enhancing the sorghum value chain in Soroti, Uganda. South African Journal of Agricultural Extension, 45(1).

Fahmi , M K M , Dafa-Alla , D-A M , Kanninen , M & Luukkanen , O. 2018. Impact of agroforestry parklands on crop yield and income generation: case study of rainfed farming in the semi-arid zone of Sudan. Agroforestry Systems, vol. 92 , no. 3 , pp. 785-800. https://doi.org/10.1007/s10457-016-0048-3

FAO. (2023). The State of Food and Agriculture 2023. Revealing the true cost of food to transform agrifood systems. Rome.

Faure, G., Blundo-Canto, G., Devaux-Spatarakis, A., Le Guerroué, J. L., Mathé, S., Temple, L., Toillier, A., Triomphe, B., & Hainzelin, E. (2020). A participatory method to assess the contribution of agricultural research to societal changes in developing countries. Research Evaluation, 29(2), 158–170. https://doi.org/10.1093/reseval/rvz036

Gewa, C. A., Onyango, A. C., Obondo Angano, F., Stabile, B., Komwa, M., Thomas, P., & Krall, J. (2019). Mothers' beliefs about indigenous and traditional food affordability, availability and taste are significant predictors of indigenous and traditional food consumption among mothers and young children in rural Kenya. Public Health Nutrition, 22(16), 2950–2961. https://doi.org/10.1017/S1368980019001848

Giné, X., & Yang, D. (2007). Insurance, Credit, and Technology Adoption: Field Experimental Evidence from Malawi (SSRN Scholarly Paper 1062407). https://papers.ssrn.com/abstract=1062407

Harris, J., Tan, W., Raneri, J. E., Schreinemachers, P., & Herforth, A. (2022). Vegetables for Healthy Diets in Low- and Middle-Income Countries: A Scoping Review of the Food Systems Literature. Food and Nutrition Bulletin, 43(2), 232–248. https://doi.org/10.1177/03795721211068652

Hassanally, S., Naicker, A., & Singh, E. (2020). Snack Development for School Feeding Programs in Africa: A Scoping Review. International Journal of Environmental Research and Public Health, 17(14), Article 14. https://doi.org/10.3390/ijerph17144967

Hotz, C., Loechl, C., de Brauw, A., Eozenou, P., Gilligan, D., Moursi, M., Munhaua, B., van Jaarsveld, P., Carriquiry, A., & Meenakshi, J. V. (2012). A large-scale intervention to introduce orange sweet potato in rural Mozambique increases vitamin A intakes among children and women. The British Journal of Nutrition, 108(1), 163–176. https://doi.org/10.1017/S0007114511005174

Jägermeyr, J., Müller, C., Ruane, A. C., Elliott, J., Balkovic, J., Castillo, O., Faye, B., Foster, I., Folberth, C., Franke, J. A., Fuchs, K., Guarin, J. R., Heinke, J., Hoogenboom, G., Iizumi, T., Jain, A. K., Kelly, D., Khabarov, N., Lange, S., … Rosenzweig, C. (2021). Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. Nature Food, 2(11), 873–885. https://doi.org/10.1038/s43016-021-00400-y

Jerop, R., Dannenberg, P., Owuor, G., Patience, M., Kimurto, P., Willkomm, M., & Tups, G. (2018). Factors affecting the adoption of agricultural innovations on underutilized cereals: The case of finger millet among smallholder farmers in Kenya. African Journal of Agricultural Research, 13, 1888–1900. https://doi.org/10.5897/AJAR2018.13357

Kamenya, S. N., Mikwa, E. O., Song, B., & Odeny, D. A. (2021). Genetics and breeding for climate change in Orphan crops. Theoretical and Applied Genetics, 134(6), 1787–1815. https://doi.org/10.1007/s00122-020-03755-1

Kpaka, H. M., Wossen, T., Stein, D., Mtunda, K., Laizer, L., Feleke, S., & Manyong, V. (2022). Rural schools as effective hubs for agricultural technology dissemination: Experimental evidence from Tanzania and Uganda. European Review of Agricultural Economics, 49(5), 1179–1215. https://doi.org/10.1093/erae/jbab028

Kubuga, C. K., Bantiu, C., & Low, J. (2023). Suitability and Potential Nutrient Contribution of Underutilized Foods in Community-Based Infant Foods in Northern Ghana. Nutrients, 15(11), Article 11. https://doi.org/10.3390/nu15112593

Lipper, L., DeFries, R., & Bizikova, L. (2020). Shedding light on the evidence blind spots confounding the multiple objectives of SDG 2. Nature Plants, 6(10), Article 10. https://doi.org/10.1038/s41477-020-00792-y

Longvah T, Ananthan R, Bhaskarachary K, Venkaiah K. (2017). Indian Food Composition Tables 2017. National Institute of Nutrition, Hyderabad. https://www.ifct2017.com/frame.php?page=home

Low, J. W., Arimond, M., Osman, N., Cunguara, B., Zano, F., & Tschirley, D. (2007). A food-based approach introducing orange-fleshed sweet potatoes increased vitamin A intake and serum retinol concentrations in young children in rural Mozambique. The Journal of Nutrition, 137(5), 1320–1327. https://doi.org/10.1093/jn/137.5.1320

Mabhaudhi, T., Chimonyo, V. G. P., Hlahla, S., Massawe, F., Mayes, S., Nhamo, L., & Modi, A. T. (2019). Prospects of orphan crops in climate change. Planta, 250(3), 695–708. https://doi.org/10.1007/s00425-019-03129-y

McMillan, K., Corr, S., Manko, K., Fereno, C., Feryo, M., Shah, N., Caffrey, R., & Herz, L. (Eds.). (2022). Acceptability of nutritious children's foods developed for markets in Sierra Leone. African Journal of Food, Agriculture, Nutrition and Development.

McMullin, S., Njogu, K., Wekesa, B., Gachuiri, A., Ngethe, E., Stadlmayr, B., Jamnadass, R., & Kehlenbeck, K. (2019). Developing fruit tree portfolios that link agriculture more effectively with nutrition and health: A new approach for providing year-round micronutrients to smallholder farmers. Food Security, 11(6), 1355–1372. https://doi.org/10.1007/s12571-019-00970-7

McMullin, S., Stadlmayr, B., Mausch, K., Revoredo-Giha, C., Burnett, F., Guarino, L., Brouwer, I. D., Jamnadass, R., Graudal, L., Powell, W., & Dawson, I. K. (2021). Determining appropriate interventions to mainstream nutritious orphan crops into African food systems. Global Food Security, 28, 100465. https://doi.org/10.1016/j.gfs.2020.100465

Porciello, J., Coggins, S., Mabaya, E., & Otunba-Payne, G. (2022). Digital agriculture services in low- and middle-income countries: A systematic scoping review. Global Food Security, 34, 100640. https://doi.org/10.1016/j.gfs.2022.100640

Rosenzweig, C., Ruane, A. C., Mutter, C. Z., Mencos Contreras, E., & Moscuzza, A. (2021). Overview of AgMIP Regional Integrated Assessment. In Handbook of Climate Change and Agroecosystems (1–2, pp. 3–13). WORLD SCIENTIFIC (EUROPE). https://www.worldscientific.com/doi/abs/10.1142/9781786348791_0001

Stewart, Z. P., Pierzynski, G. M., Middendorf, B. J., & Prasad, P. V. V. (2020). Approaches to improve soil fertility in sub-Saharan Africa. Journal of Experimental Botany, 71(2), 632–641. https://doi.org/10.1093/jxb/erz446

Tadele, Z. (2019). Orphan crops: Their importance and the urgency of improvement. Planta, 250(3), 677–694. https://doi.org/10.1007/s00425-019-03210-6

Trait prioritization in crop breeding programs: A scoping review on tools and methods. (2023, March 31). https://doi.org/10.21203/rs.3.rs-2548847/v1

van Dijk, M., Morley, T., Rau, M. L., & Saghai, Y. (2021). A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. Nature Food, 2(7), Article 7. https://doi.org/10.1038/s43016-021-00322-9

van Zonneveld, M., Kindt, R., McMullin, S., Achigan-Dako, E. G., N'Danikou, S., Hsieh, W., Lin, Y., & Dawson, I. K. (2023). Forgotten food crops in sub-Saharan Africa for healthy diets in a changing climate. Proceedings of the National Academy of Sciences, 120(14), e2205794120. https://doi.org/10.1073/pnas.2205794120

Verger EO, Savy M, Martin-Prével Y, Coates J, Frongillo E, Neufeld L et al. Healthy diet metrics: a suitability assessment of indicators for global and national monitoring purposes. Geneva: World Health Organization; 2023. Licence: CC BY-NC-SA 3.0 IGO.

Vidigal, P., Romeiras, M. M., Monteiro, F., Vidigal, P., Romeiras, M. M., & Monteiro, F. (2019). Crops Diversification and the Role of Orphan Legumes to Improve the Sub-Saharan Africa Farming Systems. In Sustainable Crop Production. IntechOpen. https://www.intechopen.com/chapters/68083

Vincent A, Grande F, Compaoré E, Amponsah Annor G, Addy PA.et al. 2020. FAO/INFOODS Food Composition Table for Western Africa (2019) User Guide & Condensed Food Composition Table/Table de composition des aliments, FAO/INFOODS. https://www.fao.org/documents/card/en?details=ca7779b

Wineman, A., Ekwueme, M. C., Bigayimpunzi, L., Martin-Daihirou, A., de Gois V. N. Rodrigues, E. L., Etuge, P., Warner, Y., Kessler, H., & Mitchell, A. (2022). School Meal Programs in Africa: Regional Results From the 2019 Global Survey of School Meal Programs. Frontiers in Public Health, 10. Scopus. https://doi.org/10.3389/fpubh.2022.871866

Annex

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Lecturer, Faculty of Science, Department of Plant Biology, University of Yaoundé

Dr. Cary Fowler,
Special Envoy for Global Food Security, U.S. Department of State

Catherine Bertini,
Managing Director, The Rockefeller Foundation

Cynthia Rosenzweig,
Senior Research Scientist, NASA GISS

David Laborde,
Director for Agrifood Economics Division, FAO

Dilys Sefakor MacCarthy, Associate Professor, University of Ghana

Doris Rittenschober,
Food composition consultant, FAO

Leigh Ann Winowiecki,
Global Research Leader, Soil and Land Health, World Agroforestry; Co-lead, Coalition of Action 4 Soil Health (CA4SH)

Edmond Totin,
Social Scientist,
World Vegetable Center (West Africa)

Emily Fredenberg, Project Manager, Global Nutrition Security, The Rockefeller Foundation

Emmanuel Okogbenin,
Director, Program Development & Commercialization, African Agricultural Technology Foundation (AATF)

Endale Amare, Senior Researcher of Food and Nutrition Sciences and Program Leader at the Food Science and Nutrition Research Directorate, Ethiopian Public Health Institute

Enoch G. Achigan Dako,
Professor, Genetics and Plant Breeding and Head, Genetics, Biotechnology and Seed Science Unit, Faculty of Agricultural Sciences, University of Abomey-Calavi

Eric Yirenkyi Danquah,
Professor, University of Ghana

Fekadu Fufa Dinssa,
Vegetable Breeder, World Vegetable Center (Eastern and Southern Africa)

Fernanda Grande,
Nutrition Officer, Food and Nutrition Division, FAO

George Bigirwa,
Deputy Vice President, AGRA

Gina Kennedy,
Director of Research, Translation and Impact for the Periodic Table of Food Initiative (PTFI) and Principal Scientist, Alliance Bioversity International and CIAT

Giulia Muir,
Forestry Consultant, FAO

Godfrey Bahiigwa,
Director of Agriculture and Rural Development, African Union Commission

Gracian Chimwaza,
Executive Director, Information Training & Outreach Centre for Africa (ITOCA)

Hailu Tefera Wordofa,
Agriculture Development Officer, Bureau for Resilience and Food Security (RFS), USAID

Harish Gandhi,
Dryland Legumes and Cereals Breeding, CIMMYT

Ivan Landers,
Cropping Systems Agronomist, FAO

Jaron Porciello,
Associate Professor of the Practice, University of Notre Dame

Jean Baptiste Bahama,
Production and Protection Officer, Africa Region, FAO

Jennifer Le Blond,
Director, US, Science & Innovation Network (SIN)

Jessica Fanzo,
Professor of Climate and Director of the Food for Humanity Initiative, Columbia Climate School, Columbia University

Jingyuan Xia,
Director, Plant Production and Protection Division, FAO

John Benedict (J.B.) Cordaro,
Special Representative Food Security, Nutrition and Safety, Mars, Incorporated

John de la Parra,
Director, Food Initiative,
The Rockefeller Foundation

John Ulimwengu,
Senior Research Fellow, IFPRI

Jose Rafael Guarin,
Postdoctoral research scientist, Center for Climate Systems Research, Columbia University, NASA Goddard Institute of Space Studies (GISS)

Joseph Korley Clottey,
International Centre for Evaluation and Development

Julia Sibiya,
Plant Breeding Professor,
UKZN, South Africa

Justina Serwaah Owusu,
Lecturer of Nutrition, University of Ghana, Legon-Accra

Kevin Karl,
Research Associate, Center for Climate Systems Research (CCSR), Columbia University

Lew Ziska,
Associate Professor, Environmental Health Sciences, Mailman School of Public Health, Columbia University

Lindiwe Majele Sibanda,
System Board Chair,
CGIAR System Organization

Luigi Guarino
Chief Scientist, Crop Trust

Lynnette Neufeld,
Director, Food and Nutrition Division, FAO

Maarten Van Zonneveld,
Head of Genetic Resources, World Vegetable Center

Marc Corbeels,
Senior Researcher, French Agricultural Research and International Cooperation Organization (CIRAD)

Máximo Torero-Cullen,
Chief Economist, FAO

Maya Rajasekharan,
Managing Director of the Africa Region, Alliance of Bioversity International and CIAT; and Director of Strategy Integration and Engagement, Periodic Table of Food Initiative (PTFI)

Michel Edmond Ghanem,
Senior Scientist, CIRAD

Moez Amri,
Professor, Genetics and Plant Breeding, UM6P

Namukolo Covic,
Director General's Representative to Ethiopia, ILRI

Oluwole (Wole) Fatunbi,
Ag Director of Research and Innovation, FARA

Patricia Masikati,
Agroforestry Systems Scientist, CIFOR-ICRAF

Pauline Scheelbeek,
Associate Professor in Planetary Health & Nutritional Epidemiology, London School of Hygiene & Tropical Medicine

Pierre Irénikatché Akponikpe,
Laboratory of Hydraulics and Environmental Modeling (HydroModE-Lab) Faculty of Agronomy, University of Parakou, Republic of Benin

Purvi Mehta,
Senior Advisor of the Global Growth and Opportunities Division, Bill and Melinda Gates Foundation

Racine Ly,
Director of Data Management, Digital Products, and Technology, AKADEMIYA2063

Ramni H. Jamnadass,
Theme Leader: Biodiversity and Tree Genetic Resources Principal Scientist, World Agroforestry (CIFOR-ICRAF)

Reginald Annan,
Associate Professor, Kwame Nkrumah University of Science and Technology

Richard Mkandawire,
Africa Director, Alliance for African Partnership (AAP), Adjunct Professor, Lilongwe University of Agriculture and Natural Resources (LUANAR)

Rob Bertram,
Chief Scientist, Bureau for Resilience and Food Security, USAID

Robert Asiedu,
Emeritus Director, International Institute of Tropical Agriculture (IITA)

Robert Delve,
Lead Global Technical Advisor (Agronomy), IFAD

Roberto O. Valdivia,
Assistant Professor, Senior Researcher, Department of Applied Economics, Oregon State University, Co-Leader of AgMIP's Regional Economics Team

Roy Steiner,
Senior Vice President, Food Initiative, The Rockefeller Foundation

Selena Ahmed,
Global Director of the Periodic Table of Food Initiative (PTFI), American Heart Association

Simone Passarelli,
Policy Advisor, U.S. Department of State

Sithembile (Thembi) Mwamakamba,
Director of Policy Research and Analysis, Food, Agriculture and Natural Resources Policy Analysis Network (FANRPAN)

Sussy Munialo,
Post-doctoral fellow, ARUA Centre of Excellence in Sustainable Food Systems, University of Pretoria

Tafadzwa Mabhaudhi,
Professor, Climate Change, Food Systems and Health, London School of Hygiene and Tropical Medicine

Tom van Mourik,
Global Advisor Food Systems, Helen Keller International

Vieshnavi Rattehalli,
Foreign Affairs Officer, Office of Global Food Security, U.S. Department of State

Wilson Hugo,
Agricultural Engineer, FAO

Zerihun Tadele,
Professor, Institute of Plant Sciences, University of Bern

African Union

AgMIP

AOCC

Food and Agriculture Organization of the United Nations

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