

Steps to transform African opportunity crops into reality crops

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Reliance on a few staple crops makes global agriculture vulnerable to climate shocks, biodiversity loss and nutrition gaps. The Vision for Adapted Crops and Soils (VACS), a global initiative to build resilient food systems, addresses this imbalance by modernizing market orientation, breeding, and capacity for opportunity crops such as amaranth, Bambara groundnut, finger millet, okra, pigeon pea, sesame, and taro. We advocate for a business unusual approach characterized by market guided prioritization and long-term breeding strategy, led by grassroots science networks. VACS applies lessons from major crop programs to translate potential into scalable impact.

Global food systems face a crisis of uniformity, characterized by overreliance on a narrow set of staple crops, primarily maize, rice, and wheat^{1,2}. This lack of diversity is risky in light of increasing climate variability^{3,4}, contributes to soil degradation^{5,6}, and ignores shifting consumer demands⁷. In parallel, a wide array of traditional crops, also referred to as orphan or forgotten crops, although we choose to call them “opportunity crops”, remains underutilized and under-researched despite their importance and potential value to millions of farmers⁸ and consumers.

Opportunity crops include cereals, pulses, oil-crops, fruits, nuts, tuber crops, and vegetables that are adapted to local agro-ecologies through longstanding traditional cultivation practices^{9,10}. Their potential extends beyond climatic resilience: they can improve dietary diversity^{11,12}, generate higher incomes, often for women and

marginalized producers¹³, and contribute to soil health and biodiversity. In Nigeria alone, okra production value is estimated above USD 2.4 billion annually, ranking the country second globally behind India¹⁴, demonstrating the economic importance of this crop. Sesame cultivation has surged in several African countries, including Sudan, Tanzania, and Nigeria, driven by international demand¹⁵. Sub-Saharan Africa is estimated to produce 21% of the global pigeon pea crop, representing about USD 3.3 billion, in a market that is expected to double in value between now and 2035¹⁶. Yet despite their economic and cultural significance, these crops have been marginalized in research, breeding, and investment agendas, resulting in stagnant productivity compared to steady yield gains in staple food and internationally traded cash crops^{4,17–19}. A systematic review of orphan crop interventions in Sub-Saharan Africa shows that success depends on

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coordinated action across breeding, seed systems, markets, and consumer demand, yet few initiatives have intentionally aligned these elements within a coherent product development framework²⁰. The same trend is true for human capital, where most students and early career scientists focus on major staples rather than opportunity crops²¹.

The Vision for Adapted Crops & Soils (VACS), launched by the U.S. Department of State in 2023 and co-hosted by the International Maize and Wheat Improvement Center (CIMMYT) and the Food and Agriculture Organization (FAO), aims to address this situation and transform opportunity crops into reality crops²². Opportunity crops have recently attracted a steep rise in scientific coverage^{9,11,23–25}. At the crop level, detailed roadmaps have articulated how opportunity crops can be improved through integrated breeding pipelines that link germplasm management, genomics-assisted selection, participatory evaluation, and value chain development²⁶. In parallel, genome-enabled initiatives such as the African Orphan Crops Consortium have substantially strengthened the scientific foundations for these crops by generating reference genomes, molecular tools, and breeder capacity²⁷. Together, these efforts demonstrate that both conceptual frameworks and technical enablers for opportunity crop improvement are now in place; however, their translation into coordinated, market-oriented product development pathways that deliver large-scale livelihood impacts has remained limited. Concrete examples of breakthrough innovations comparable to semi-dwarf wheat and rice²⁸, orange-fleshed sweet potato²⁹ or drought-tolerant maize⁴, with important impacts on the livelihoods of farmers on a large scale, have not yet materialized.

This Perspective builds on the 2024 *Nature Communications* Editorial, which emphasized that the “efficient genetic improvement of orphan crops cannot follow the old path”³⁰. We describe a seven-step business unusual plan for turning opportunity crops into reality crops.

We draw on early success stories from the first two years of implementation across VACS crops (Supplementary Notes 1–7), to illustrate how market-guided prioritization, modernized breeding pipelines, and coordinated partnerships translate the business unusual principles into concrete progress.

Step 1: Look before you leap – wisely choose the opportunity crops for investment

Before initiating a breeding program, recruiting breeders, and making the first crosses, considerable thought was given to selecting the initial cohort of opportunity crops. The choice of crops for VACS breeding investments began with around 150 candidates, which were reduced to 60 “long-listed” ones, leading to 20 crops that were compared via climate crop modeling³¹. The prioritization process, described by Fredenberg et al.³², engaged 80 international experts from disciplines such as genetics, agronomy, nutrition, social sciences, economics, and climatology. Through a series of technical workshops, these experts used a set of criteria: nutritional quality (FAO nutrition data), climate resilience (climate–crop modeling by AgMIP³¹ and Zonneveld et al.³³), adoption feasibility (Havos.ai analyses of seed systems, markets, and extension)³¹, and economic impact (FAO assessments) to prioritize the candidate crops. Seven opportunity crops were selected for the VACS-Breeding component: amaranth (*Amaranthus spp.*), Bambara groundnut (*Vigna subterranea*), finger millet (*Eleusine coracana*), okra (*Abelmoschus esculentus*), pigeon pea (*Cajanus cajan*), sesame (*Sesamum indicum*), and taro (*Colocasia esculenta*). These were chosen to encompass diversity in crop categories, including cereals, legumes, vegetables, roots and tubers, and oilseeds.

Figure 1 synthesizes the comparative assessment of the seven crops as reported in Karl et al.³¹ against selected reference crops (soybean as reference for Bambara groundnut, pigeon pea and sesame, maize for finger millet, cassava for taro, tomato for okra, and

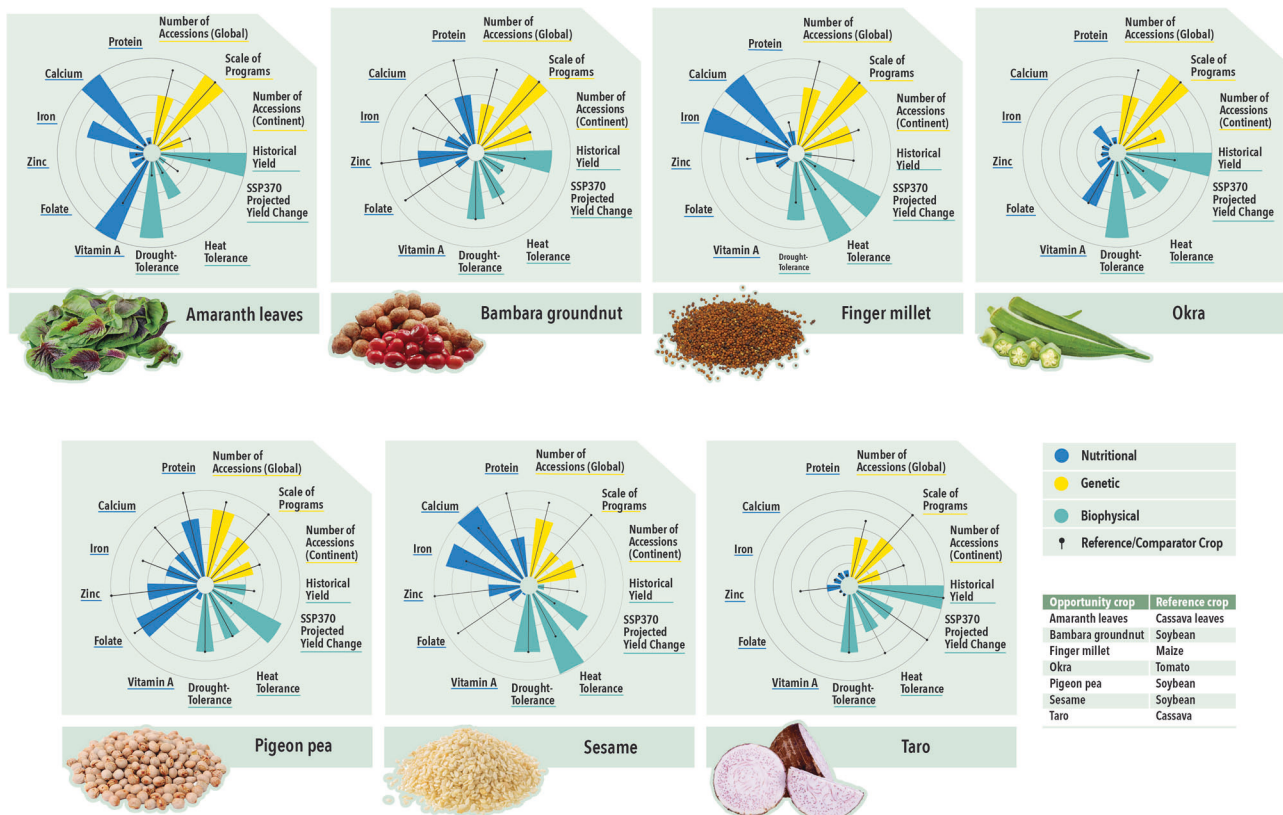


Fig. 1 | Integrated nutritional, genetic, and biophysical profiles of the seven VACS crops. Adapted from Karl et al.³¹, licensed under CC BY 4.0 (<https://creativecommons.org/licenses/by/4.0/>). Changes were made.

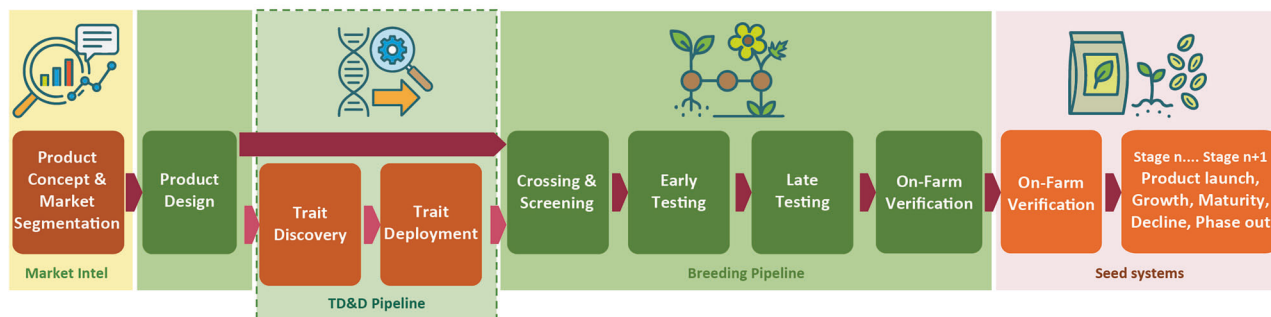


Fig. 2 | The CGIAR product development process was implemented for opportunity crops.

cassava leaves for amaranth leaves). Each radar chart integrates nutritional attributes (concentrations of protein, calcium, iron, zinc, folate, and vitamin A), genetic attributes (global and continental genetic resources and the scale of breeding programs), and biophysical attributes (historical and projected yield performance, drought, and heat tolerance). The figure highlights the potential of these crops to contribute to nutritious, climate-adapted food systems, while cautioning that they lag behind selected reference crops in key genetic assets.

Step 2: No romance – trust, but verify the market opportunities

As laid out in the product development process (Fig. 2), which is widely used across CGIAR breeding programs³⁴, the second step is to use market intelligence information to identify market segments and develop target product profiles (TPPs) that are feasible, in-demand, and impactful for targeting by breeding programs. Market intelligence research describes opportunities to secure or increase value from innovations in product design and delivery³⁵, and begins with understanding the needs of the important stakeholders. Investments in opportunity crops must be targeted to data-supported, validated opportunities, avoiding assumptions that they should and will be adopted by farmers. This requires an understanding of their requirements for processing and value in diverse markets, including export and high-end markets. On the other hand, smallholder farmers operate in complex farming systems that depend on crops for multiple purposes, including food, fodder, soil fertility, and income; ignoring any of these farmer priorities can limit adoption and erode potential impact^{36,37}. The goal of market intelligence research is to avoid one-size-fits-all approaches and channel efforts toward market segments with the greatest potential for impact³⁸, based on evidence of market size, demand, future trends, and opportunities for value creation.

It is useful to recognize that some characteristics of VACS crops, such as nutritional profiles and climate resilience characteristics, are likely to be under-incentivized by current market conditions. This failure of the market to directly compensate farmers for providing goods with socially desirable attributes contributes to their under-provision³⁹. For characteristics such as nutritional value (some VACS crops are rich in key micronutrients, dietary fiber, and protein), the absence of price incentives may reflect insufficient consumer awareness of these attributes, challenges in assuring uniform quality in the market, or negative associations with taste or preparation characteristics. Similarly, above-average resilience to drought, heat stress, and marginal soil conditions of VACS crops may be imperceptible to farmers and undervalued by markets because these benefits are unevenly realized across locations and seasons. As a result of these challenges to uniformly quantify their value, profitability signals systematically undervalue the broad welfare contributions of orphan crops. For both cases, i.e., nutritional and climate resilience values,

breeding can help mitigate market and crop failures by lowering production costs or increasing productivity at a given production cost.

A major challenge in assessing the market size and demand for opportunity crops is the lack of reliable data. Although agricultural censuses and nationally representative farm surveys have generated insights on smallholder farming in Sub-Saharan Africa, significant gaps remain. Opportunity crops are often underrepresented because many, such as taro or amaranth, are mainly grown in home gardens rather than in surveyed field plots. Even when cultivated in cropping systems, they are frequently omitted from reports as minor components in complex systems. Additionally, since many of them are mostly traded in informal local markets, there is limited data about production and market volumes. Finally, because these crops receive less attention in agricultural research and development, they are rarely captured in project-based data collection efforts.

Given the lack of market intelligence data, the prioritization process relies heavily on country-level Product Design Teams (PDTs) consisting of researchers, policymakers, seed companies, processors, and farmers⁴⁰. Such multi-stakeholder engagement aligns with recent calls for participatory, transdisciplinary approaches to opportunity crop research that emphasize inclusive priority setting across the value chain⁴¹. The PDTs apply structured frameworks to identify and prioritize market segments⁴² and define TPPs, which describe the breeding targets for each essential or “nice to have” trait⁴³. TPPs align breeding objectives with user needs, production constraints, and regulatory requirements. For example, as a result of a sesame PDT meeting in Tanzania, a TPP was designed for white early-maturity sesame, the country’s largest market segment (estimated at 1.3 million hectares). During crop discussions, 5 “essential to improve” traits were identified, encompassing traits that are required for varietal acceptance, while 10 were considered “nice to have”, capturing additional attributes that enhance value but are optional. Across the 7 VACS-Breeding opportunity crops, more than 20 country-level PDTs have met, resulting in 46 identified market segments, of which 20 were prioritized based on market demand, with TPPs developed for each.

Breeding strategies must be dynamic and agile to integrate emerging opportunities. For example, vegetable pigeon pea⁴⁴ is a rapidly expanding market segment tied to urbanization, while taro offers new prospects through processing for gluten-free cookies, chips, and flour (Supplementary Note 1). Similarly, sesame markets are diversifying into high-value products for cooking oil, medicine, and cosmetics⁴⁵ (Supplementary Note 6), and red-leaf amaranth shows potential as a highly nutritious and fast-growing vegetable⁴⁶. Overall, the market for amaranth is expanding, with the leaf recognized as highly nutritious, and the grain as protein-rich and gluten free⁴⁷. Paying attention to such signals, for example by making certain quality traits essential, allows breeding programs to anticipate change and align genetic innovation with future demand.

Agility in breeding also demands that perceived opportunities (Step 1) be validated against real market data and signals. Through

annual engagements with the PDTs, supported by data from fieldwork, market research teams confirm which trends justify breeding investment. In this way, programs remain demand-responsive and minimize the risk of investing based on idealism.

Step 3: Establish a grassroots network of partners

The VACS-Breeding project selected lead institutions and principal investigators for each crop following a structured approach that began with a call for proposals, inviting institutions engaged in target crops to submit their interest to lead and present their concepts. The African Plant Breeders Association (APBA) was consulted to identify potential lead institutions that were then contacted and invited to submit leadership proposals. A selection committee evaluated the proposals and interviewed the short-listed applicants, asking them to describe their value proposition, proposed target product profiles, expected short-term outcomes, key collaborators, and overall vision of success for the crop.

The selected VACS crop lead institutions (a full list of partners, with names and abbreviations, is provided in Fig. 3) include three CGIAR Centers (CIMMYT, ICRISAT, and IITA), two National Agricultural Research and Extension System (NARES) institutions (Tanzania's TARI and Nigeria's NIHORT), and WorldVeg. All institutions that submitted leadership proposals, and others known to have active improvement programs in the respective opportunity crop, were invited to participate in the collaborative crop research and improvement network, resulting in strong, co-owned platforms for breeding innovation and variety development. The overall VACS-Breeding program is co-led by a VACS-Breeding Leadership Team consisting of two members from each crop team (one from the lead institution and at least one from a NARES), which meets monthly to discuss progress, identify challenges, and plan future activities. Inclusive leadership with local experts in a crop network that co-defines a shared vision and strategy, with a strong focus on impact, is a key step on a business-unusual path. One of the first tasks of the leadership team was to consult the entire team to draft, revise, and vote to agree on their mission and vision (Box 1). This shared mission and vision define why the team exists, and their co-definition was an important step towards co-ownership and commitment to achieve impact.

Step 4: Don't re-invent the wheel - learn from the major crops

Major staple crops have benefitted from decades of research investment and strong international breeding teams, resulting in the development and adoption of proven technologies and methods that deliver consistent rates of genetic gain to the market. Many of these approaches are crop-agnostic, and VACS-Breeding teams are adopting, adapting, validating, and implementing them to modernize and accelerate progress in opportunity crop breeding. Learnings and best practices from major crops are being applied and adapted throughout the product development pipeline (Fig. 2).

Trait discovery and dissection

VACS is leveraging methods, tools, and approaches developed in maize, tomato, rice, and other crops⁴⁸. Trait discovery entails the

identification of new and useful genetic variation within breeding populations, germplasm collections, or wild relatives, frequently using high-throughput phenotyping and multi-omics methods and approaches⁴⁹. Trait dissection focuses on elucidating the genetic and molecular foundations of these traits by pinpointing the underlying loci, alleles, or genes, and comprehending their inheritance patterns and biological functions⁵⁰. Collectively, these processes lay the foundation for the development of molecular markers, genomic selection models, and targeted breeding strategies to accelerate crop improvement.

Genebank germplasm, wild relatives, collections from farmers, recombinant inbred lines (RILs), multi-parent advanced generation intercross (MAGIC) populations, and diverse genetic populations⁵¹ are being used. The availability of MAGIC populations for amaranth, RILs for Bambara groundnut, and the development of recombinant inbred lines and a diversity panel for okra are valuable resources for trait discovery and mapping, marker development, and deployment for functional traits. These genetic resources are being phenotyped (germplasm characterization) under diverse agro-ecologies across partner institutions. Although breeding populations exist for amaranth and Bambara groundnut, progress has been constrained by difficult floral biology and limited institutional expertise in reliable crossing. Targeted capacity-strengthening workshops addressed these bottlenecks by equipping breeders with practical crossing skills to enable population development for trait discovery and cultivar improvement (Supplementary Notes 2 and 3). For crops such as okra and pigeon pea, which have hybrid breeding potential, defining heterotic groups is essential to efficiently harness hybrid vigor and accelerate the development of superior hybrids.

Standardized phenotyping protocols are being developed for each species, and data are being stored and managed in agreed, shared systems, mainly the Enterprise Breeding System (EBS). EBS is an open-source breeding informatics platform developed by CGIAR⁵² to manage the large datasets from major crop research programs. It integrates germplasm management, trial design, phenotypic and genotypic data, and analytics into a single system, enabling breeders to streamline workflows, improve data quality and data sharing, and integrate multiple streams of breeding data. The integration of high-throughput phenotyping tools and methods, leveraging the experience with major crops, is ongoing, utilizing unmanned aerial vehicles (UAVs) equipped with multispectral cameras. For instance, the VACS-Breeding okra team is using UAVs to measure normalized difference vegetation index, normalized difference water index, and phenotyping root system architecture (e.g., root orientation, volume, surface area, and total length) that may prove helpful in breeding for enhanced drought tolerance.

Genomic resources

Phenotypic and genotypic data are being assembled to enable trait discovery and dissection, allele mining, marker-assisted breeding, and other genomics applications in opportunity crops. Several genotyping platforms are available from other crops' research efforts, including single-nucleotide polymorphism (SNP), genotyping arrays, next-generation sequencing (NGS)-based platforms, and PCR-based genotyping (Kompetitive Allele Specific PCR - KASP). Genomic resources, including high-quality whole genome sequences, are available for a few, though not all, opportunity crops.

Pigeon pea, amaranth, and sesame have relatively extensive genome sequence data available for use in discovery and trait dissection. Pigeon pea was among the first orphan crops to be sequenced using de novo sequencing⁵³, and a recent high-quality genome produced for the ancient landrace 'D30' unveiled a dominant haplotype that may prove useful in breeding for 100-seed weight⁵⁴. Current genomic resources for amaranth include high-quality genome assemblies of cultivated (*A. hypochondriacus* and *A. cruentus*⁵⁵), and weedy species (*A.*

BOX 1.

VACS-breeding

Mission: Create collaborative state-of-the-art, impactful, and sustainable improvement programs for opportunity crops in Africa

Vision: Healthier lives and improved livelihoods for Africa through improved opportunity crops and agricultural systems

Finger millet and taro have rapidly growing genomic resources. In taro, de novo genome assemblies for the Hawaiian landrace ‘Moi’ and the Chinese cultivar ‘Longxiangyu’ provide a framework for surveying taro genotypes for resistance to leaf blight, bacterial wilt, and drought tolerance. For finger millet, the recently published reference-quality, chromosome-resolved assembly for the cultivated Kenyan accession KNE 796⁶¹ opens opportunities for VACS partners to discover and dissect diversity for resistance to blast, tolerance to drought and heat, and higher mineral content (e.g., Ca). The VACS breeding team recently sequenced the genome of finger millet, specifically the popular variety U15 in Tanzania and Malawi (also known as Maridadi in Kenya and Seremi 2 in Uganda), to serve as a reference genome. Five more lines are being sequenced to develop the first finger millet pangenome.

Okra (*A. esculentus*) has two publicly available long-read genome sequences^{62,63}. Marked variation in chromosome number across *Abelmoschus* species⁶⁴ necessitates the development of additional high-quality reference genomes, particularly for related species that constitute key reservoirs of biotic stress resistance (e.g., *A. caillei*, *A. moschatus*, and *A. manihot*). Concurrently, an *A. esculentus* pangenome capturing intraspecific diversity would provide a critical platform for genomics-assisted okra improvement. The generation of genomic resources for Bambara groundnut requires further investments, as only a draft reference sequence and no fully resolved chromosome-scale reference genome is available^{65,66}.

Reference genomes and pangenomes are foundational tools in plant breeding, enabling the identification and introgression of genetic variation linked to traits such as drought tolerance, nutritional quality, and disease resistance.

Breeding pipeline design

Because of scarce or short-term funding, breeding efforts for opportunity crops have typically been trait-based, seeking quick solutions to complex challenges⁶⁷. Short-term funding horizons drive short-term planning and a quick fix approach, with no time to design and implement overarching crossing structures or coordinated breeding pipelines⁶⁸. This approach has failed to address complex traits or develop robust breeding pools to sustain long-term improvement of crop performance and resilience.

Step 2, which convened and consulted PDTs to describe what products are needed (TPPs), and Step 3, which identified who and co-defined why they will develop these products, are essential preconditions for Step 4, which defines how the opportunity crop varieties are being developed. As we will briefly describe, the how required re-tooling to adapt and adopt methods developed and implemented in the major crops for use in product-based pipelines (Fig. 2) for opportunity crops. Among the necessary preconditions to developing effective, modern opportunity crop breeding programs, which were considered in selecting the seven VACS-Breeding crops (Step 1; Fig. 1) and the lead institution for each crop (Step 3), are the availability of adequate genetic variance and a working knowledge of the crop’s

biology. With all the ingredients (Step 1-3) in place, opportunity crop breeding requires revisiting current breeding approaches and defining optimized breeding strategies based on quantitative genetic principles.

Recycling time refers to the period to complete one breeding cycle and initiate the next, encompassing all steps from crossing and selection to generating new parents. Under-invested breeding programs are often characterized by long recycling times, and in some cases, recycling never truly happens, because the same germplasm is repeatedly used as parents over many years. Other factors, such as a limited number of crosses per cohort, a small number of lines evaluated per cross, and relaxed selection intensity, further contribute to inefficiencies in under-invested or short-term breeding pipelines. Table 1 lists the comparison of 2023 reality for three breeding programs, as assessed by and among network partners, with two optimized scenarios co-designed for co-implementation in modernized breeding programs for opportunity crops (finger millet, in this example).

VACS breeding programs have optimized their pipelines to incorporate genomic selection within the next 1-3 years. Genomic selection is effective for improving complex traits (e.g., yield and drought), which are governed by many loci with small effects. Genomic selection also enables selection at early generations (F4 or earlier) before phenotypic evaluation, shortening breeding cycles and improving selection accuracy⁶⁹. Breeding programs have identified base populations for the new regional pipelines based on agronomic and yield trials, genomic, and pathology data. In contrast to the short-term, trait-based pipelines described in the introductory paragraph of this section on pipeline design, base populations provide the initial genetic variability for selection and long-term improvement in response to changing environments and breeding objectives⁷⁰.

Figure 4 graphs the simulated genetic gains for the five programs described in Table 1, assuming closed pipelines, i.e., with zero introduction of new genetic sources. Optimized regional pipelines with genomic selection offer five-times larger expected genetic gain in the first five years compared to current programs. We note that, for sustained, long-term gains, this strategy must use algorithms such as optimum cross selection or judicious introduction of new variation to avoid excessive erosion of genetic variance.

For the success of such data-driven strategies, modern breeding programs use analytical tools and decision support systems to optimize breeding scheme parameters and resource allocation before implementing changes, and for managing various streams of breeding data. As mentioned earlier, VACS breeding programs have adopted EBS to support these activities. Deterministic models and stochastic simulation tools enable evaluation of alternative scenarios for crossing block design, population sizes, selection intensity, and resource allocation^{71,72}, e.g., see Fig. 4. These tools allow breeding programs to test modifications virtually before implementing them in practice, identifying key parameters to maximize genetic gain within budget constraints^{73,74}.

Table 1 | Finger millet breeding parameters: current programs and optimized scenarios with or without genomic selection (2023)

Program	Average cycle time (years)	Crosses per cohort (number)	Population size (lines evaluated per cross)	Total pipeline size (lines)	Lines recycled (number)	Selection intensity (%)	Stage 1 trial locations (number)
Country A	10	10	10	100	16	16	4
Country B	23.4	105	4	400	22	6	1
Country C	10	30	13	400	8	2	2
Optimal regional without GS	2	50	30	1500	30	2	50 (sparse*)
Optimal regional with GS	2	80	56	4500	30	<1	50 (sparse*)

* Sparse testing of new recombinant lines generated after making new elite x elite crosses and as generally described in Werner et al.⁹⁴.

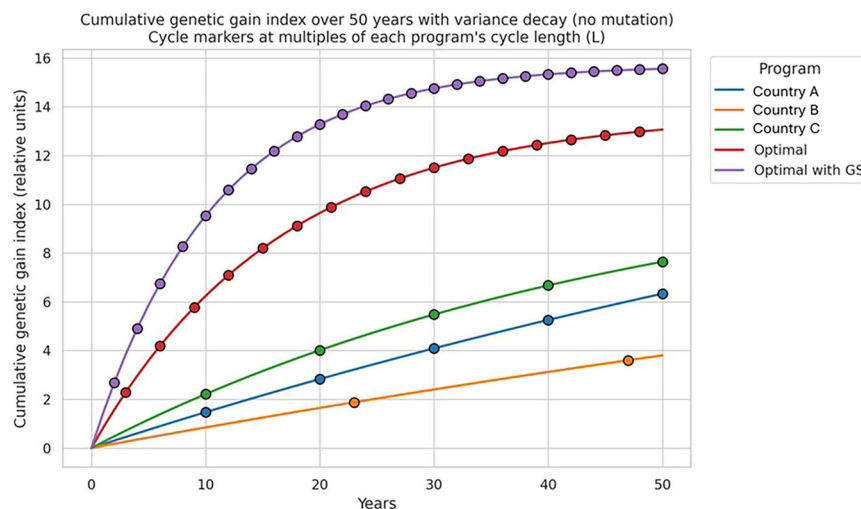


Fig. 4 | Simulated genetic gain of three current finger millet programs and optimized pipelines with and without genomic selection (GS). Simulations assume a closed system with no introduction of new genetics.

Advanced analytics and data management systems, clearly defined product needs (Step 2) help ensure a consistent and systematic approach for identifying parents for recycling and products or varieties for scaling. Stage-gate advancement systems, with data-driven decision criteria at each gate, enable transparent, accountable product development⁷⁵. Each gate is a decision point with criteria based on TPPs, for example, minimum level of disease resistance, percent yield advantage over relevant checks, and feedback from the value chain on processing traits. This systematic approach reduces resource waste on poorly performing material and ensures alignment with TPPs throughout the breeding cycle. Advancement of materials from late-stage on-farm trials to deployment in seed systems is undertaken by the PDT in each country (Supplementary Note 5).

When combined with additional tools and technologies (see four examples below), the above approaches further enhance the effectiveness of the VACS opportunity for crop breeding. Quality assurance and quality control (QA/QC) protocols are essential for maintaining genetic integrity throughout the breeding pipeline and ensuring farmer confidence in improved varieties. Quality control checkpoints at multiple stages, from crossing block through seed multiplication, prevent the accumulation of genetic impurities. In VACS breeding programs, routine F₁ verification using SNP markers is in place for finger millet, pigeon pea, and amaranth, while other crops are initiating the procedure. Molecular marker-based purity testing is faster and often more reliable than traditional grow-out tests conducted during seed production; therefore, it is useful during handoffs from breeder to early-generation seed (EGS), and EGS to certified seed production.

Rapid generation advance (RGA) techniques accelerate the development of homozygous lines by advancing multiple generations per year under controlled conditions, enabling faster variety development. The feasibility of deploying RGA in orphan crop breeding programs was recently reviewed⁷⁶, and open-access speed breeding protocols for chickpea, pigeon pea, and finger millet are available^{77,78}. Because controlled-environment (photoperiod, temperature, humidity) greenhouses are expensive, VACS is democratizing the technique by optimizing RGA protocols for use in existing screenhouses or fields (field-based RGA).

A global shift toward the use of modern statistical methodologies occurred with the widespread adoption of linear mixed models (LMMs) that employ restricted/residual maximum likelihood (REML) for variance component estimation and best linear unbiased prediction (BLUP) for genotypic value prediction. This transformation revolutionized plant breeding by naturally accommodating unbalanced

datasets, incorporating genetic relationships through pedigree information, and modeling complex variance-covariance structures. These advanced methods have proven particularly advantageous for VACS opportunity crops, enabling more accurate selection when breeding programs face limited resources, incomplete factorials, and spatially heterogeneous trial conditions.

High-throughput phenotyping technologies may enable precise evaluation of breeding material at scale, improving selection decisions while reducing costs. AI-powered image-based phenotyping using smartphones and computer vision models reduces subjectivity and costs associated with field phenotyping, and allows partners to participate in developing the models⁷⁹. Over one million images for finger millet, pigeon pea, and other crops have been collected in Kenya for AI model training⁸⁰ over multiple iterations for each crop and trait for deploying them in breeding programs. Once validated models are available, they will enable real-time, in-field trait predictions to support rapid breeding decisions. Access to computing power to perform such & other analyses is a key requirement, and we rely on shared computing resources and an analytics pipeline (e.g., BioFlow) that are already available for breeding major crops.

Cognizant of the unsatisfactory history of short-term, quick-fix approaches in opportunity crop breeding, and aware of the (above-described) opportunities to adopt modernizing methods from major crop research investments, the VACS breeding crop teams were invited to propose prioritized investments to modernize their breeding programs. Five broad areas of opportunity were identified (Fig. 5), from which each crop team prioritized two opportunities (Table 2). The prioritized opportunities were funded and are being implemented by each team in pursuit of the mission (Box 1) to create state-of-the-art, impactful, and sustainable breeding programs, i.e., investing in long-term rather than quick-fix solutions to the complex challenges of making opportunity into reality crops. These opportunities were pragmatic investments that helped optimize operations or address gaps in genomic data.

Step 5: Plan and build the path to impact

A focus on achieving impact requires building a path for the market demanded (Step 2), efficiently developed (Step 4) crop varieties to reach farmers, and for their produce to reach markets. This begins by including key stakeholders in the product definition (PDTs that define TPPs), involving them and others in various stage gate advancement decisions, and preparing the handover to seed producers and subsequent value chain actors. Fortunately, VACS has a seed systems team

Modernizing Breeding of Opportunity Crops

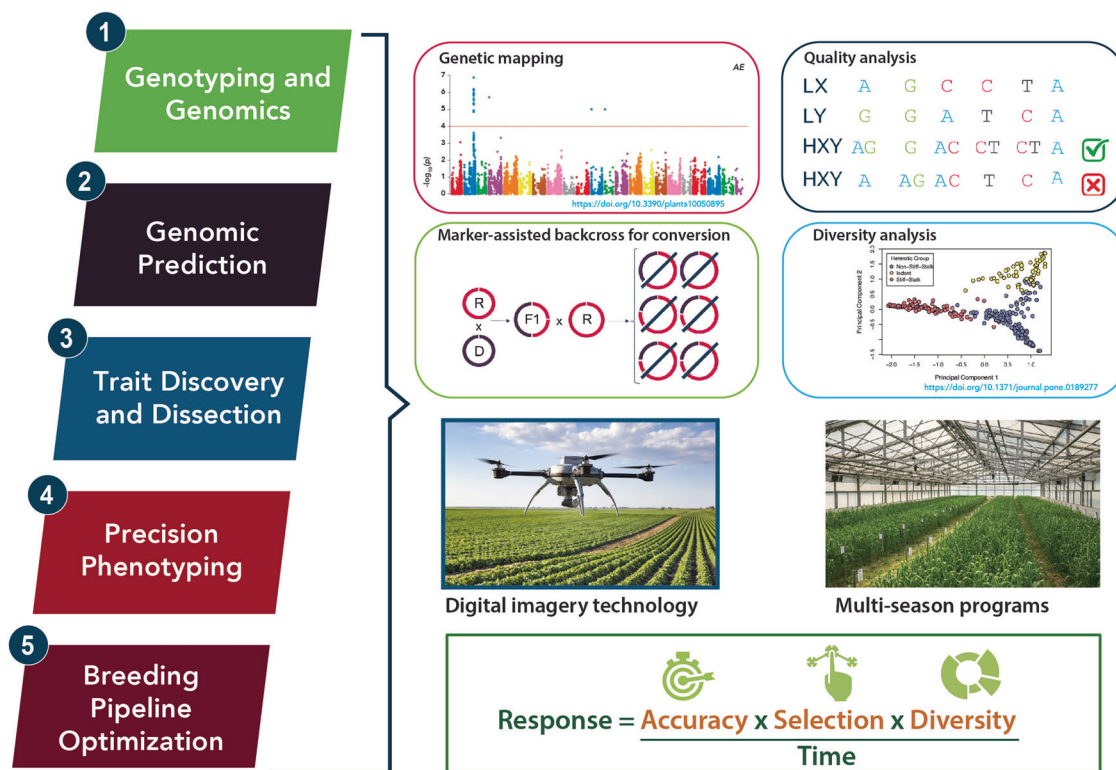


Fig. 5 | Options for modernizing breeding programs.

Table. 2 | Prioritized breeding modernization investments per crop

Crop	Prioritized breeding Modernization investments
Bambara groundnut	Genotyping for diversity analysis Screenhouses for pollination and accelerated breeding
Finger millet	Genotyping for trait discovery Rapid generation advancement greenhouse
Sesame	Developing genomic resources UAVs with multispectral sensors for high-throughput phenotyping
Pigeon pea	Genomic for parent selection and QC applications Irrigation for precision and off-season growing facilities
Okra	Genotyping of okra collection and pangenome development UAV-based multispectral phenotyping & root phenotyping
Amaranth	Biochemical analysis of quality traits for breeding population Establish facilities & protocols for pathogen identification & screening
Taro	Genotyping for diversity analysis & breeding pipeline management Screenhouses to increase the success rate of breeding crosses

(VACS-Seed Systems) with whom the crop breeding teams can partner for impact.

The VACS-Seed Systems component applies a Public-Private-Producer Partnership (4P) model that links public research, private-sector investment, and farmer participation to accelerate varietal turnover and adoption⁸¹⁻⁸³. It builds on Africa's pluralistic seed landscape, which spans formal, informal, and intermediate systems. The formal system, comprising public research, regulatory agencies, and registered seed firms, produces certified seed under quality control. The informal system, based on farm-saved and locally exchanged seed, remains the dominant source for 70-80% of smallholders⁸³. Between these lies an intermediate domain, including community-based seed production schemes, quality declared seed (QDS), and local seed businesses⁸⁴ which link local availability with assured minimum quality. QDS is seed produced by trained local multipliers and marketed under a simplified, locally supervised inspection system that verifies minimum quality standards, typically with less stringent requirements than fully certified seed⁸⁵.

The 4P approach redefines coordination across these systems by aligning the strengths of each actor. CGIAR and NARES generate early

generation seed (EGS) and provide technical oversight; small and medium-sized enterprises (SMEs) and agro-dealers handle multiplication and marketing; organized farmers serve as multipliers and demand creators; and development partners and financiers support enabling investments and policy reforms. Studies of EGS models across Africa show that sustainability depends on clear institutional roles, risk sharing, and transparent pricing of breeder and foundation seed⁸⁶⁻⁸⁸.

Even where improved varieties and certified or QDS are present, adoption and productivity gains are often constrained by uneven last-mile access to advisory services, particularly in remote and semi-arid zones where public extension is thinly staffed and operational budgets are limited⁸⁹. Addressing this requires targeted investment in extension functions covering seed quality literacy, variety-specific agronomy, and market and enterprise skills. VACS operationalizes this through an extension approach that combines public extension, village-based advisors, agro-dealers, and digital tools, ensuring that high-quality seed is paired with the knowledge and market linkages needed for sustained adoption at scale. Demand creation relies on demonstration plots (Supplementary Note 4), village-based advisors,

and small seed packs (100–500 g), which have proven highly effective in lowering entry barriers and accelerating adoption^{90,91}. These approaches deliver fast adoption growth at minimal cost per farmer. Foresight and market intelligence guide demand forecasting and climate-risk mapping, aligning seed production with anticipated uptake.

Recent experiences in Kenya, Tanzania, Ghana, Senegal, Malawi, and Zambia demonstrate how rapid scaling can occur when improved seed, information, and market access converge^{82,92}. Many of these examples promoted women and youth as seed producers, traders, and advisors. Women-led firms like Dryland Seed in Kenya exemplify women-led entrepreneurship, while Ghana's campaigns reserved 40% of small packs for women farmers. Youth engagement was enhanced through digital platforms and training on business management and financial literacy. Similar gender-transformative efforts under demand-led seed systems and innovation platforms have shown that women representation improves varietal adoption and household welfare^{83,93}.

Step 6: Invest in people to secure the present and the future

The VACS movement invests in graduate scholar and professional fellowship programs, complementing extensive capacity-building efforts such as the African Orphan Crops Consortium (AOCC), the West Africa Centre for Crop Improvement (WACCI), and the African Centre for Crop Improvement (ACCI), among others. Unlike business as usual, however, these scholars and professionals work within the VACS-Breeding crop teams, addressing pressing challenges and opportunities for improvement of opportunity crops. The 28 graduate (10 MSc and 18 PhD) scholars embedded in VACS-Breeding are nationals of 8 countries, are registered in 16 African universities, and each conduct research on current knowledge gaps while gaining expertise on one of the 7 opportunity crops; 4 work with amaranth, 7 with Bambara groundnut, 4 with finger millet, 3 with okra, 2 with pigeon pea, 6 with sesame, and 2 with taro. Thesis research topics involve 1) application of genomic tools in trait discovery (e.g., shattering resistance in sesame, Striga resistance in finger millet, enhanced micro-nutrient content in amaranth, and reduced cooking time in Bambara groundnut), 2) use of modern tools and methods to enhance breeding efficiency (e.g., application of gene editing in finger millet, use of drones for high throughput phenotyping in okra), and 3) use of genomic data for trait discovery, marker-assisted or genomic selection in each of the seven crops. Several studies integrate participatory and farmer-centered approaches to strengthen breeding pipelines, conserve genetic diversity, and develop climate-resilient varieties suited to local production systems across sub-Saharan Africa.

The VACS capacity sharing approach seeks to secure the present and the future of opportunity crops for Africa by focusing research attention on today's key bottlenecks and opportunities, building research programs at African universities, and developing a new generation of scientists equipped to advance opportunity crops.

Step 7: Value diversity – it is not one or the other

The intended solution to today's crisis of uniformity in agriculture is not to replace the major staples with opportunity crops. Most consumers enjoy eating and rely on mega-crops - maize, wheat, and rice - as important components of their nutrition. The goal of VACS is not to replace the crops that underpin global food security, but to diversify production and consumption options in ways that enhance climate resilience, nutritional diversity, and livelihood opportunities. Integrating opportunity crops into existing rotations, intercropping, and mixed farming systems allows farmers to manage risk more effectively, improve soil health, and make fuller use of local agroecological niches throughout the year. The integration of opportunity crops into farming systems and consumers' diets also has cultural value, honoring tradition and indigenous knowledge, based on market intelligence and science.

Concluding remarks and future perspectives

The seven-step plan being implemented by the VACS-Breeding team does not follow the old path of doing the same - seeking quick fix, simple, and low-cost solutions to complex challenges - and hoping for a better outcome. The business unusual approach that we have described has the following defining features to realize the potential of opportunity crops:

Long-term approach: To achieve and sustain genetic gains like those in major crops, VACS is investing in modern tools and cutting-edge methods to achieve efficiencies and effectiveness across all stages of the breeding pipelines. There is no shortcut or single tactic for long-term success.

Market driven: A rigorous approach was applied to select a small number of crops for substantial breeding investments. Market and social economists, informed by diverse stakeholders, are validating and prioritizing continued investments.

Grassroots network: Local scientists and stakeholders define the vision, the breeding product profiles, the crop-wise modernization priorities, and the opportunities to build long-term capacity for impact. Local context and expertise lead the project.

While VACS-breeding builds on the best science and practices from the major crops, we've also highlighted that opportunity crops have gaps to close before they can match the rates of progress that are achieved by the major crops: data, genome sequencing, speed breeding methods, and human resource gaps, to name a few. Between the lines of this perspective, perceptive readers will find a profound message of gratitude to funders of this work, who realize that sustained investment will be critical for opportunity crops to become reality crops, shoulder to shoulder with today's major crops.

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Author contributions

P.R., E.G.A.D., and K.V.P.: led concept development, writing of the manuscript, and revision; M.A.T.A., J.C., H.D., A.C.H., S.K., A.M.G., T.M.N., C.O.O., J.S.: contributed to writing original draft and revision; H.G., V.R.B., M.N., J.B., B.C., C.E., P.G., D.I., H.M., D.M., J.O., R.S., D.E.T., E.N.Y.:

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Competing interests

The authors declare no competing interests.

Additional information

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