CGIAR project on

RTB Breeding

Annual Technical Report 2023

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This publication has been produced in close collaboration with the International Institute of Tropical Agriculture (IITA) and the CGIAR Research Initiatives on Accelerated Breeding, Breeding Resources, Market intelligence, and Seed Equal.

Acronyms

ABC	Alliance Bioversity International and CIAT
ABI	Accelerated Breeding Initiative
ARI	Advanced Research Institutions
DCT	Demand Creation Trials
EBS	Enterprise Breeding System
EGS	Early Generation Seed
GS	Genomic Selection
HIFe	High Iron
IIAM	Instituto de Investigação Agrária de Moçambique (Agricultural Research Institute of Mozambique)
IITA	International Institute of Tropical Agriculture
KPIs	Key Performance Indicators
MAS	Marker Assisted Selection
NACRRI	National Crop Resources Research Institute
NARO	National Agricultural Research Organization
NARS	National Agricultural Research Systems
NRCRI	National Root Crops Research Institute
OFT	On Farm Testing
PacBio	Pacific Biosciences
PCR	Polymerase Chain Reaction
PDT	Product Design Teams
RTB	Roots, Tubers, and Bananas
SGA	Sub Grant Agreement
SNP	Single Nucleotide Polymorphism
SOPs	Standard Operating Procedures
SSA	Sub Saharan Africa
TARI	Tanzania Agricultural Research Institute
TPE	Target Population of Environments
TPP	Target Product Profiles
TOC	Theory of Change

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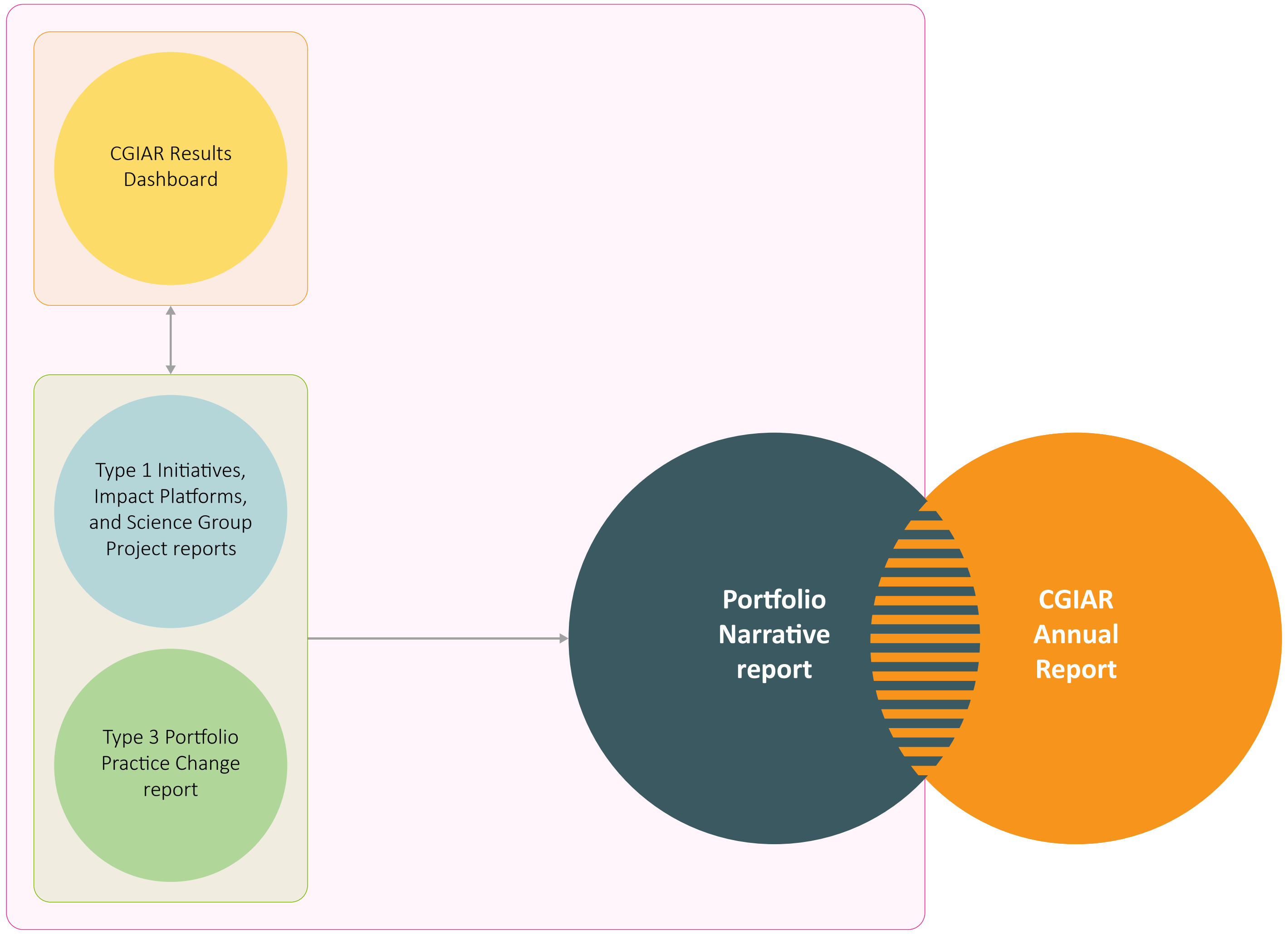
CGIAR Technical Reporting 2023

CGIAR Technical Reporting has been developed in alignment with the CGIAR Technical Reporting Arrangement. This Science Group Project (SGP) report is a Type 1 report and constitutes part of the broader CGIAR Technical Report. Each Science Group Project submits an annual Type 1 report, which provides assurance on SGP progress towards End of Project outcomes.

The CGIAR Technical Report comprises:

- Type 1 Initiative, Impact Platform, and Science Group Project (SGP) reports, with quality assured results reported by Initiatives, Platforms and SGPs available on the CGIAR Results Dashboard.
- The Type 3 Portfolio Performance and Project Coordination Practice Change report, which focuses on internal practice change.
- The Portfolio Narrative, which draws on the Type 1 and Type 3 reports, and the CGIAR Results Dashboard, to provide a broader view on Portfolio coherence, including results, partnerships, country and regional engagement, and synergies among the Portfolio's constituent parts.

The CGIAR Annual Report is a comprehensive overview of CGIAR's collective achievements, impact and strategic outlook, which draws significantly from the Technical Report products above. For 2023, the Annual Report and Technical Report will be presented online as an integrated product.



Section 1: **Fact sheet and budget**

Science Group Project name	Roots, Tubers and Banana Breeding: A Consolidated Investment
Short name	RTB Breeding
Science Group Project Lead	Hugo Campos (h.campos@cgiar.org)
Science Group	Genetic Innovation
Start – end date	1 February 2023 – 31 December 2024
Geographic scope	**Regions** East and Southern Africa · West and Central Africa **Countries** Cameroon · Colombia · Côte d'Ivoire · Ethiopia · Ghana · Kenya · Malawi · Mozambique · Nigeria · Peru · Rwanda · Sierra Leone · Tanzania, United Republic; Democratic Republic of the Congo · Uganda · Zambia
Website link	https://rtbbreeding.cgiar.org/

EXECUTIVE SUMMARY

The CGIAR Science Group Project (SGP) on Roots, Tubers and Banana Breeding: A Consolidated Investment (RTB Breeding), which is CGIAR's first SGP, represents a step change in the way research is supported and carried out in CGIAR. In addition to developing technological innovations and mainstreaming modernized breeding approaches for banana, cassava, potato, sweetpotato and yam, this Project aims to bring about a shift in mindsets and along a change management journey, from traditional breeding efforts focused on individual crops to breeding for the whole group of root, tuber and banana crops.

Among our key achievements in the breeding domain, the following stand out: demonstrable progress on all determinants of genetic gains, using the breeder's equation as compass; implementing a gender research agenda with multiple points along breeding pipelines; integrating food quality/preferences into target product profiles (TPPs) to an extent previously unobserved; developing marker-trait associations and molecular breeding technologies required to sustain the routine implementation of predictive breeding, an area where cassava is at the forefront, in banana, sweetpotato, potato and yam; increasing focus on accelerating parent recycling in addition to developing superior varieties; and updating features of BreedBase, the digital management system at the core of RTB Breeding. Moreover, progress toward developing pangenomes, particularly in banana but also in sweetpotato, represents a milestone for polyploid crops.

At the operational level, a main achievement was updating TPPs in all RTB crops and instituting product design teams in several countries in close interaction with national programs. Establishing subregional CGIAR-national agricultural research system (NARS) breeding networks in banana and potato are also prime examples of achievement.

It is, however, in the area of change management where the most progress has been attained within a period of just 11 months. Five large CGIAR transdisciplinary breeding teams were established that are committed to learning how to work together effectively and how to take full ownership and assume accountability without relinquishing their individual identities or crop expertise. These teams have established novel, equitable partnerships with multiple national programs in sub-Saharan Africa and other research organizations and universities and are able to self-organize for decision-making.

Our journey since February 2023 has had its challenges, learnings, and shortcomings, but it has been a rewarding and productive one, able to generate a shared sense of ownership and accountability for the success of all RTB crops — not just individual ones — that would serve smallholder farmers by delivering superior crop varieties with higher rates of adoption.

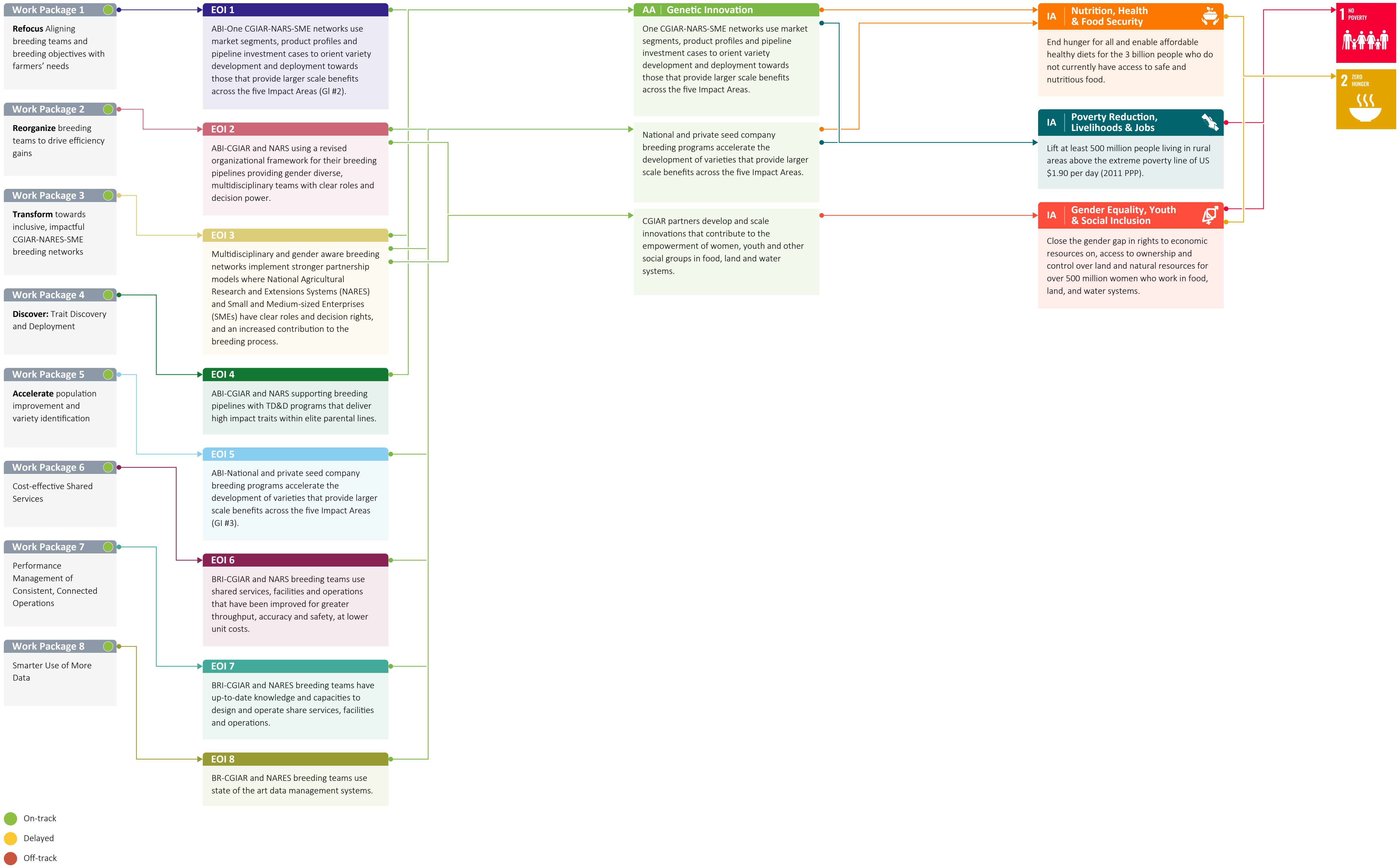
	2023	2024
APPROVED BUDGET	**$13.22M**	$16.45M

Banana bunch, Tanzania.
Credit: Rony Swennen (IITA)

Section 2: **Progress on science and towards End of Initiative outcomes**

Science Group Project-level theory of change diagram

This is a simple, linear, and static representation of a complex, non-linear, and dynamic reality. Feedback loops between this and other Initiatives' theories of change are excluded for clarity.



EOI	End of Initiative outcome
AA	Action Area
IA	Impact Area
SDG	Sustainable Development Goal

Note: A summary of Work Package progress ratings is provided in Section 3.

Advanced Sweetpotato Trials at Bvumbwe Research Station in Malawi. Credit Lennin Musundire,DARS

Summary of progress against the theory of change

RTB Breeding represents more than just mainstreaming modern breeding approaches across banana, cassava, potato, sweetpotato, and yam. It is effecting organizational as well as technological innovations with its shifts in mindsets from a traditional single-crop breeding effort to a multi-crop breeding effort. Together with integrating changes guided by quantitative genetics, RTB Breeding programs are integrating in TPPs food quality traits missing in earlier breeding efforts. This gradual departure from previous efforts encourages intellectual and practical cross-pollination between and among teams of breeders and scientists, with breeding work on any one RTB crop able to tap into the knowledge, expertise, and learnings of research on the other RTB crops, which creates new opportunities for research advances and professional growth.

RTB Breeding aspires to better serve smallholder farmers by delivering greater genetic gains on their farms, accelerating farmer adoption of new varieties, establishing effective and efficient CGIAR-NARS breeding networks, and attracting and retaining top talent. Our work is underpinned on extensive field research conducted in 15 African countries.

During 2023, RTB Breeding helped to develop new breeders and scientists, particularly from Africa, with 3 students completing their graduate studies, 21 continuing with their academic programs, and 5 new students pursuing graduate studies. Historical CGIAR breeding of RTB crops aimed to help alleviate poverty through breeding efforts focused on agronomic (yield, climate resilience) and defensive (pest and disease resistance) traits. Our results, while also strongly anchored to poverty reduction goals, are also aligned with the goals of gender equality, nutritional well-being, and climate change adaptation and mitigation.

To make progress in increasing genetic gains, our body of work closely aligns to the diverse components of the breeder's equation, a framework used to predict responses to selection, since steady progress toward higher genetic gains requires that several of such components be acted on concurrently.

For example, RTB Breeding developed standard operating procedures (SOPs) for screening resistance to weevils in banana; we trained yam researchers on participatory breeding in on farm trials (OFT) and more than 140 breeders and scientists from national programs and IITA hubs on cassava breeding data management tools and systems in Zambia, Côte d'Ivoire, Tanzania, Democratic Republic of the Congo, and Nigeria; and we strengthened human capacity in advanced potato breeding in East Africa.

Progress with selection intensity was achieved by imposing desired gain selection indices for elite parent selection of sweetpotato in Uganda, in collaboration with the National Crops Resources Research Institute (NACRRI) and in Mozambique, in collaboration with the lnstituto de lnvestigacao, Agraria de Mocambiqe (IIAM), whereas to reduce breeding cycle time, genomic cross-performance predictions were implemented in yam for population improvement and faster parent recycling.

To accelerate progress toward its desired outcomes, RTB Breeding selected Matooke and mchare banana hybrids in Uganda and Tanzania, respectively, through advancement meetings informed by TPPs and Demand Creation Trials (DCT) to create demand and accelerate adoption of improved varieties of cassava, sweetpotato and yam.

To further our specific commitment to empower women smallholder farmers through superior varieties, RTB Breeding identified prioritized cassava traits for social inclusion and gender equity in East and Western Africa and mainstreamed gender-related traits in sweetpotato breeding in Uganda. This gender-related research and progress has been achieved along breeding pipelines, starting with increasing consideration and inclusion of gender-related traits in TPPs, improving digital tools to collect gender and quality/preferences datasets, and significantly expanding use of the "comparison of technology options" (tricot) and OFT research methods across cassava, sweetpotato and yam work in addition to including more countries in this work, such as the Democratic Republic of the Congo.

During a "Pause and Reflect" meeting, which is part of CGIAR's adaptive management process, RTB Breeding staff and other relevant experts conducted a thorough analysis of the Project's theory of change (TOC). Progress achieved in 2023 toward our TOC is consistent with expectations, and the original assumptions underpinning the TOC of RTB Breeding remain sound and appropriate. The Project made some adjustments in the way some of its outputs and outcomes are articulated, as well as small changes and remapping of its outputs and/or indicators, to drive the long-term changes it seeks. These adjustments were made to increase the Project's synergies with CGIAR Initiatives working on genetic innovations, to increase the efficiencies of the Project's Work Packages, and to better articulate the logic of the Project's impact pathways.

Although RTB Breeding was approved as a SGP only in February 2023, so that just 11 months of its implementation are being reported here, the volume and quality of the Project's results, as well as the progress it has already made toward its End of Project outcomes (EOPOs), are on track to meet expectations.

Progress by End of Project Outcome

EOPO 1: REFOCUS breeding teams and objectives to better align with farmer needs

Throughout 2023, all RTB crops underwent a rigorous review, with adjustments made as needed and country-specific market insights and inputs from key stakeholders included in TPPs. All TPPs were uploaded to CGIAR's Breeding Portal and are informing breeding decisions and helping breeders to identify priority traits on which to focus their genetic gain efforts.

EOPO 2: REORGANIZE breeding teams to drive efficiency gains

RTB Breeding pipelines were mapped onto stage-gate processes, with each stage carefully defined and associated with specific tasks. The stage-gate approach has been adopted by all RTB crops and is being aligned to the most recent guidelines of the Accelerated Breeding Initiative. This helps advance superior clones tailored to market demand and breeding program objectives. Key stakeholders involved at all stages were selected and capacity gaps identified for all RTB crops. Key performance indicators (KPIs) were developed to track product advancement and management processes and to assess the effectiveness of breeding programs/pipelines in delivering against agreed-upon TPPs.

EOPO 3: TRANSFORM CGIAR, national agricultural research and extension systems, and small- and medium-sized enterprises into inclusive and impactful breeding networks

Multiple product design teams were jointly established with national programs for banana (Kenya, Tanzania, Uganda), potato (Ethiopia, Rwanda, Kenya), and sweetpotato (Uganda, Rwanda) in East Africa. In West Africa, such teams were organized in yam (Nigeria, Ghana, Côte d' Ivoire, Benin) and cassava (Nigeria). Excellent progress was observed in both banana and potato with the launch of East African CGIAR-NARS breeding networks, which coordinate activities to meet country needs and provide smallholder farmers with superior varieties. Several short-term training courses were carried out to help national programs improve the efficiency of their development and delivery of superior varieties to end users.

EOPO 4: DISCOVER and deploy desired traits

Trait discovery and establishment of robust marker-trait associations are essential to RTB Breeding's ability to increase genetic gains. The banana team developed such associations for essential traits such as fruit filling. Multiple marker-trait associations and promising single nucleotide polymorphisms (SNPs) were developed in yam, as well as the ability to predict cross-combinations. And in cassava, large-scale genome-wide association studies (GWAS) uncovered multiple genomic regions linked to biotic stress, quality/preference, and agronomic traits.

EOPO 5: ACCELERATE population improvement and variety identification

Significant progress was made in increasing genetic gains by reducing breeding cycles and improving quality management and thereby the accuracy of the breeder's equation. Research in bananas is under way to reduce breeding cycles and accelerate elite parent recycling. In sweetpotato, genomic selection (GS) is being implemented to speed up breeding cycles in Uganda (in collaboration with NaCRRI) and Mozambique (in collaboration with IIAM). In cassava, genomic-supported recurrent selection and advancement of clones is being regularly used. In yam, genomic predicted cross-performance is mainstreamed in breeding pipelines, and one early maturing variety was released in Nigeria jointly with the National Root Crops Research Institute (NRCRI).


Cassava field in early growing phase, Nigeria. Credit: Chiedozie Egesi (IITA)

EOPO 6: BUILD cost-effective shared services

Steady progress toward first-generation banana and sweetpotato pangenomes was observed, as well as in cassava with whole genome long read sequencing to enhance GS, imputation, and facilitating the identification of genes associated with disease resistance and quality traits.

Progress was achieved regarding high throughput phenotyping tools to assess priority quality/preference traits and with spectral tools on homogeneous cassava samples such as flour, as well as with linking images with texture and color in yam, and with mealiness in sweetpotato. Early-stage research use of hyperspectral imaging for characterizing the spatial distribution of cassava root constituents looks very promising. Moreover, machine learning models tested in sweetpotato enabled automation and throughput when assessing flesh color and mealiness.

EOPO 7: ENSURE consistent, connected performance management operations

Effective, efficient, and standardized operations and cost management are seldom appreciated as trademarks of a successful breeding program, yet they play a major role in fully preservicng genetic gains through breeding pipelines that can be quickly translated onto smallholder fields. All RTB crops were developed and implemented with SOPs for specific processes and in partnership with the Accelerated Breeding Initiative. All crop work carried out costing assessments, though the sweetpotato one is unfinished. Banana teams from IITA, Uganda's National Agricultural Research Organisation (NARO) and the Tanzania Agricultural Research Institute (TARI) jointly carried out a detailed costing of matooke and mchare pipelines.

EOPO 8: MAKE smarter use of more data

Unless phenotyping operations are run under high heritability landscapes, translating genetic signal into superior varieties and higher genetic gains becomes an inefficient, daunting task. Excellent progress was achieved with advanced designs, expanded use of linear mixed models and digital data collection capabilities, and deploying bar codes and other systems to reduce preventable errors and therefore increase heritability. All CGIAR Centers and their national program partners involved in RTB crops share a key asset, BreedBase, as a centralized database management system. In 2023, its contents and features were updated for all crops and intensive capacity building efforts on BreedBase topics were made in national programs.

Potato field in Rwanda.
Credit Thiago Mendes, CIP

Section 3: **Work Package progress**

WP1: REFOCUS

On track

Work Package 1 progress against the theory of change

Organizational innovation in RTB crops involves, among other aspects, the development and alignment of breeding pipelines with specific TPPs tailored to meet the demands of distinct market segments. Throughout 2023, each RTB crop team carefully reviewed its TPPs, incorporating country-specific market insights and input from key stakeholders. For instance, matooke banana researchers prioritize yield and resistance to pests and diseases, whereas mchare banana researchers target Fusarium wilt resistance. Similarly, essential traits for cassava, yam, potato, and sweetpotato were identified based on market demands. These were uploaded to the Breeding Portal and are available for informing breeding decisions. The gender-focused team has consolidated gendered food product profiles for all RTB crops to integrate them into TPPs, making gender-relatedness visible as a gender impact area.

During 2023, product design team meetings were conducted in banana (Kenya, Tanzania, Uganda), potato (Ethiopia, Rwanda, Kenya), and sweetpotato (Uganda, Rwanda) in East Africa. In West Africa, they were organized in yam (Nigeria, Ghana, Côte d' Ivoire, Benin) and cassava (Nigeria). Stakeholders' markets were segmented and TPPs developed in alignment with these priorities, and essential traits were identified and prioritized, for instance in cassava in Nigeria, matooke bananas in Uganda, and mchare bananas in Tanzania. Similar discussions were held in yam in several West African countries, allowing for a nuanced understanding of preferences and challenges. Product development teams helped advance genetic gains for dry yield and progress with market-preferred traits to drive adoption and market penetration in several ways. First, they enabled development of targeted breeding strategies focused on enhancing essential traits identified through collaborative efforts. Second, by segmenting markets and understanding specific country priorities, breeding programs can tailor their efforts to address challenges and preferences more effectively. Third, the involvement of stakeholders across the value chain ensures that resulting varieties are not only more productive but also meet the demands of growers, processors, and consumers.

WP2: REORGANIZE

On track

Work Package 2

Output

- Pipeline specific stages gates, hand over criteria and RACI documented for CGIAR-NARES breeding teams. (Scalable Crop Product Pipeline Management). (Banana, Cassava, Potato, Sweet Potato, Yam)
- Capacity building of men and women researchers including gender intentional demand led breeding. (Banana, Cassava, Potato, Sweet Potato, Yam, Quality)

EOI 2

ABI-CGIAR and NARS using a revised organizational framework for their breeding pipelines providing gender diverse, multidisciplinary teams with clear roles and decision power.

Work Package 2 progress against the theory of change

A scalable management system was established to ensure advancement of superior clones tailored to market demand and PPTs. Breeding pipelines were mapped onto stage-gates, where each stage is carefully defined and aligns with specific tasks. Stage-gate processes are being adopted by all RTB crops and are currently being updated to align with the most recent stage-gates of CGIAR's Accelerated Breeding Initiative. After standardizing the roles and disciplines involved, key stakeholders involved at all stages were identified as well as current capacity and gaps for most RTB crops, including cassava, yam, banana, and plantain. Decision-rights mapping was done to clarify accountability and reduce complexity in decision-making in these crops, and a similar approach implemented for potato and sweetpotato. KPIs to track product advancement were developed to assess the effectiveness of breeding programs/pipelines to deliver against TPPs and to identify areas needing improvement. The cassava breeding program at NRCRI in Nigeria organized a product advancement meeting in November that provided a platform to assess the uptake and application of some of these resources. Product advancement meetings of matooke banana and mchare banana were organized, with the matooke one being led by the NARO team. The yam team institutionalized product advancement meetings in 2023.

Substantial progress was achieved regarding gender and OFT for variety release and the first visit to a gender-disaggregated cassava tricot is planned by Nigeria's variety registration committee in 2024. Furthermore, a qualitative tool has been developed to assess different social context/working conditions of men and women and to gain insights underpinning gender-driven trait preferences. OFT/tricots for variety release purposes have been further expanded to sweetpotato and yam in Nigeria and to cassava in the Democratic Republic of the Congo (the latter being established in close cooperation with the variety registration authority). The tricot citizen science/OFT research for variety release under way in cassava and planned for sweetpotato and yam gives special attention to women's representation in value chains, since women dominate these processing and marketing activities.

WP3: TRANSFORM

On track

Work Package 3

Output

- Breeding pipeline human capacity (NARS) developed. (Banana, Cassava, Potato, Sweet Potato, Yam, Quality)
- Mechanism developed/streamlined for NARs partners to co-create and for decision making (Banana, Cassava, Potato, Sweet Potato, Yam)
- Guidelines on gender diversity, and clear roles and decision rights for CGIAR, NARS and appropriate stakeholders developed. (Bananas, Cassava, Potato, Sweet Potato, Yam, Quality)

EOI 3

Multidisciplinary and gender aware breeding networks implement stronger partnership models where National Agricultural Research and Extensions Systems (NARES) and Small and Medium-sized Enterprises (SMEs) have clear roles and decision rights, and an increased contribution to the breeding process.

Work Package 3 progress against the theory of change

Significant strides made with the organization and launch of East Africa CGIAR-NARS breeding networks by banana and potato initiatives marked a crucial step in harmonizing breeding and field testing operations. These networks, focused on meeting specific country needs, aim to benefit smallholder farmers with superior varieties and to foster coordination and efficiency. Short-term training conducted for national programs during the same period was pivotal in strengthening breeding systems by covering such topics as database use, basic molecular data analysis, and multi-locational trial analysis using the 'R' statistical package; this training aimed to enhance efficiencies in developing and delivering superior varieties to end users.

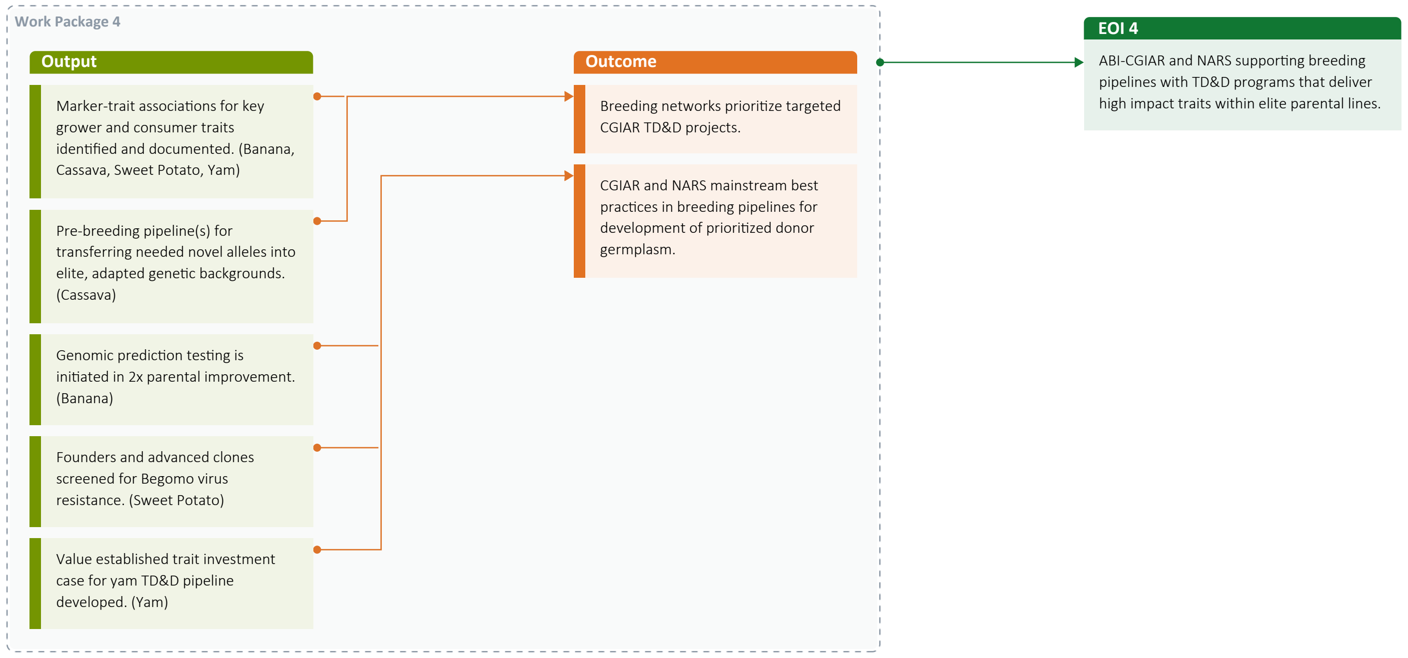
Excellent progress was also achieved in integrating gender considerations into breeding and evaluation processes. The gender team's advancements in developing an integrated gender approach spanning tricot, participatory processing evaluation, auctions, choice experiments, and food science consumer testing are delivering beyond expectations. These efforts, conducted on the same field experiments, enable optimal triangulation of breeding, food science, and social/gender data, thereby capturing tacit knowledge and preferences crucial for enhancing agricultural outcomes while keeping costs at bay.

Product design team meetings with staff of national programs played a pivotal role in East and West Africa, facilitating market segmentation and the development of TPPs. These TPPs provided clear guidance for advancing breeding materials, aligning breeding strategies with market demands and farmer needs across many countries. Such collaborative efforts ensured that the resulting products met the diverse needs of growers, processors, and consumers, ultimately contributing to food security and livelihood improvement in both regions.

These initiatives represent a concerted effort to harmonize breeding networks, enhance collaboration, and prioritize efforts to benefit smallholder farmers with superior varieties. By integrating gender considerations and aligning breeding strategies with market demands, significant progress has been made toward developing varieties able to sustain accelerated dissemination.

WP4: DISCOVER

On track

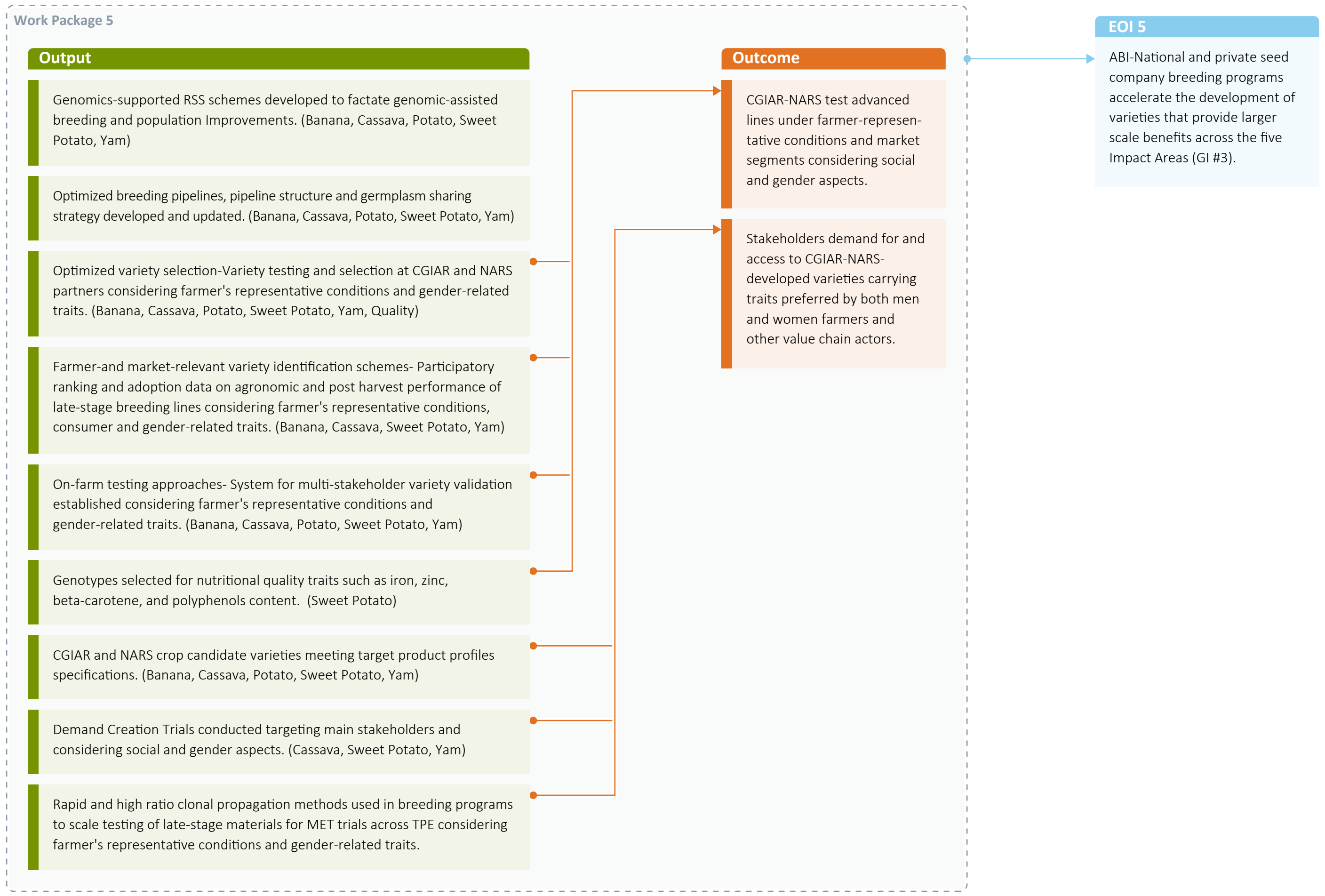


Work Package 4 progress against the theory of change

Significant progress was made in the discovery and deployment of molecular markers linked to key traits, delivering significant improvements in efficient and precise breeding strategies. In banana, for instance, molecular markers were developed for fruit filling, enabling early selection of hybrids with edible fruits, a process that previously took one to two cycles for field evaluation. This improvement allows the selection of plants at the nursery stage with potential resistance and fruit filling capacity, saving time and costs. In yam, substantial achievements were reported in modernizing efforts through the development and deployment of molecular tools. Using yam TPPs, 14 key agronomic and tuber quality traits were identified for marker-trait association studies. For marker deployment purposes, promising SNP markers were identified for 9 traits out of the 14 considered combinations, with validation of SNP markers for 7 traits. Over 3,000 genotypes from early-generation trials were selected for marker-assisted selection, and validated markers were tested for product advancement. Additionally, several markers associated with tuber food product quality were identified, linking to the food quality index. In cassava, a large-scale genome-wide association study involving more than 5,100 clones genotyped at more than 100K SNP markers uncovered a total of 41 genomic regions underlying genetic variation for 14 traits classified broadly into biotic stress (cassava mosaic disease and cassava green mite severity); quality (dry matter content and carotenoid content); and plant agronomy (harvest index and plant type). The best markers from these loci were converted to allele-specific polymerase chain reaction (PCR) assays and validated in independent populations. Cassava CGIAR-NARS breeding networks routinely deploy marker-assisted selection (MAS) in early-generation selections, especially for virus resistance, high carotenoid and dry matter contents, and low cyanogenic potential.

WP5: ACCELERATE

On track



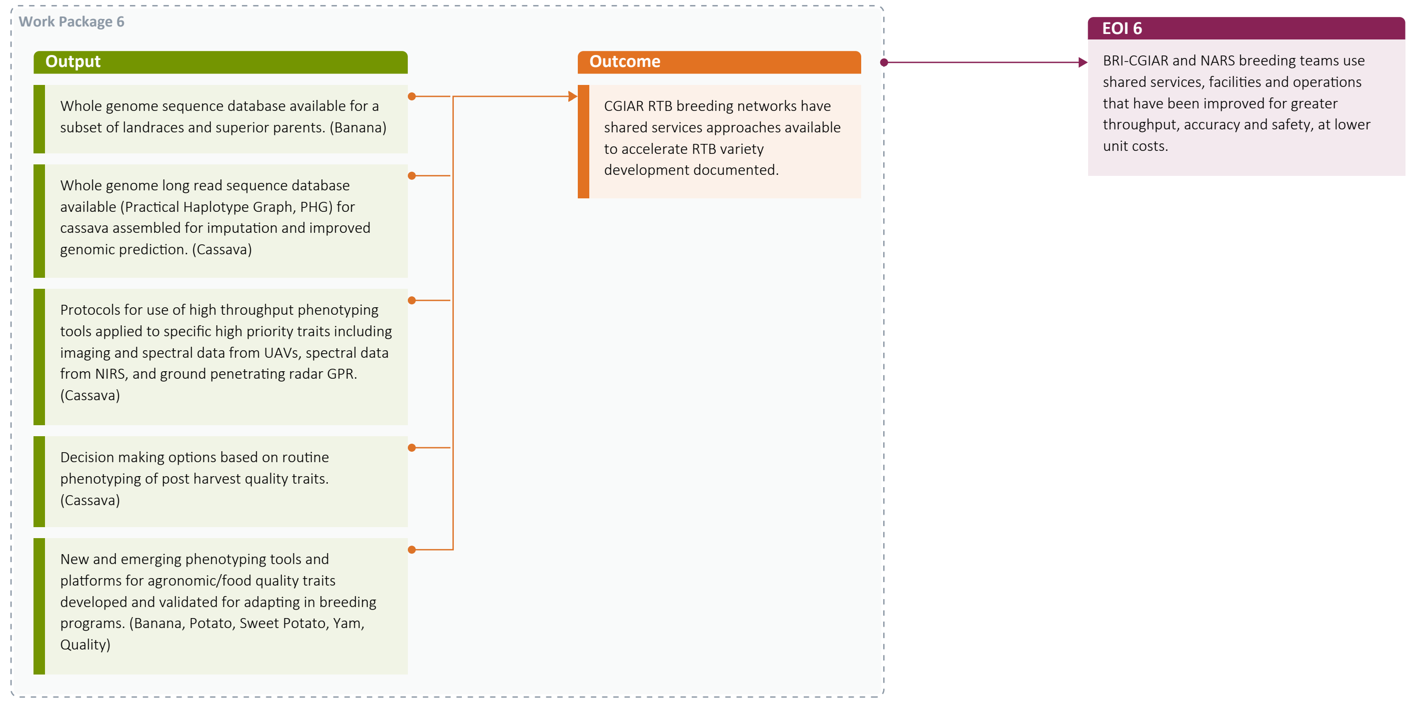
Work Package 5 progress against the theory of change

Typically, the breeding cycle of most RTB crops ranged from 5 to 15 years, partly due to long growth periods. Substantial progress toward improving genetic gains has been made by reducing breeding cycle length and/or the average age of parents and sharing elite seed. In sweetpotato, CIP has implemented selection indices to select parents for programs in Uganda and Mozambique, and genomics-supported recurrent selection is being implemented to enhance genetic gains in RTB crops within CGIAR-NARS networks to expedite breeding cycles.

Yam breeding has implemented genomic prediction cross-performance, exploiting both phenotypic and molecular datapoints to compute total genetic and breeding values of progenies from all potential mating combinations. Cassava breeding mainstreamed tools for genomic-supported recurrent selection and advancement of clones. In sweetpotato, several GS models (BLUP, RKHS, and Bayes A) were tested in training populations in Uganda, with the BLUP model with pedigree information providing the best predictions of genetic merit. Various RTB crop populations were phenotyped (to be genotyped later) for quantitative trait loci (QTL) mapping and deploying low-cost markers such as Kompetitive allele-specific PCRs to predict the transportability of QTL allelic effects. High-iron sweetpotato elite populations have been evaluated in Peru and Mozambique and genotyped to enable GS, and the sweetpotato Mwanga Diversity Panel populations in Uganda have been used for GWAS for weevil resistance traits, revealing significant hits. Banana breeding has planted the first populations to move in the same direction as other RTB crops, namely shortening breeding cycles and quicker turnover in recycling of parents. The yam team released an early maturing/bulking white yam variety in Nigeria and conducted a large set of on-farm DCTs encompassing 11 states in Nigeria and involving more than 1,500 farmers. The cassava team conducted similar demand-creation activities aimed at accelerating progress toward the Project's outcomes.

WP6: Cost-effective shared services

On track



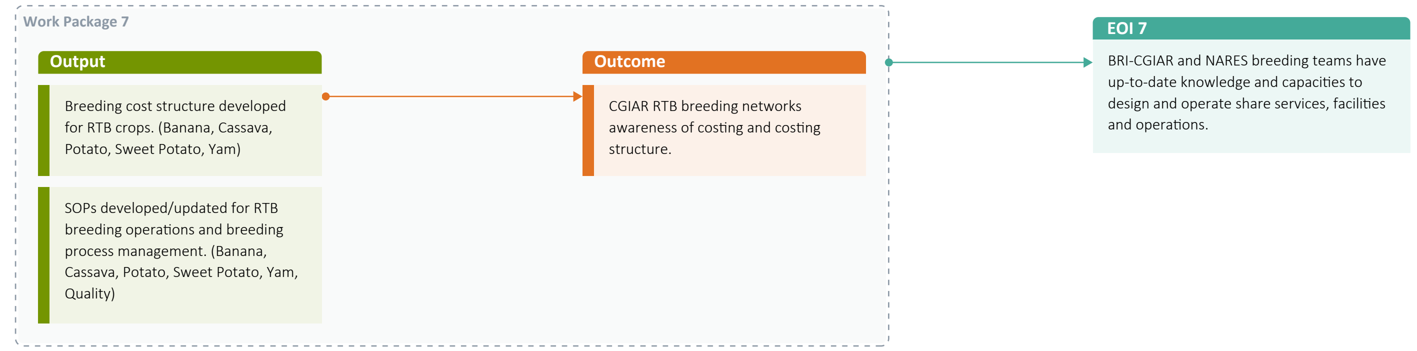
Work Package 6 progress against the theory of change

Significant progress occurred in the provision and documentation of shared services to accelerate RTB variety development. Eighteen banana varieties were sequenced in a collaboration spanning Bayer, Corteva, and the Institute of Experimental Botany at the Czech Academy of Sciences (IEB). This represents the underpinning of the banana pangenome, including plantain, matooke, and mchare, as well as wild and improved diploids. Similar progress was achieved toward the sweetpotato pangenome with genotypes Beauregard, New Kawago, Tanzania, and Irene. Whole genome assemblies in both crops are being further processed so they can be retrieved for molecular breeding approaches. In cassava, a developed Whole Genome Long Read Sequence Database is pivotal for enhancing GS efforts, imputation, and the identification of genes for disease resistance and quality traits. A total of 21 diverse and important cassava accessions were sequenced and assembled using PacBio HiFi and Hi-C technologies and 15 of such accessions are being assembled into haplotype-resolved genomes encompassing long contiguous reads, reaching imputation accuracy in a 60–90 percent range across accessions. These advancements, coupled with the use of software such as rTASSEL and rPHG, greatly facilitates the analysis of SNPs and haplotype-based analyses.

The feasibility of throughput phenotyping spectral tools to assess quality/preference traits such as dry matter, amylose, and starch on homogeneous cassava samples such as flour was demonstrated. Further, research with image analyses has demonstrated the feasibility of linking images with texture and color in yam, and with mealiness in sweetpotato. Hyperspectral imaging shows enough merit for characterizing the spatial distribution of cassava root constituents, which could enable developing indices for processing and transformation ability. Machine learning models tested in sweetpotato in Uganda increased throughput when assessing flesh-color and mealiness and retting rates in cassava, an important characteristic for cassava fufu processing. To improve routine and dependable use of breeding programs, SOPs were developed for quality/preference traits included in TPPs.

WP7: Performance Management of consistent, Connected operations

On track



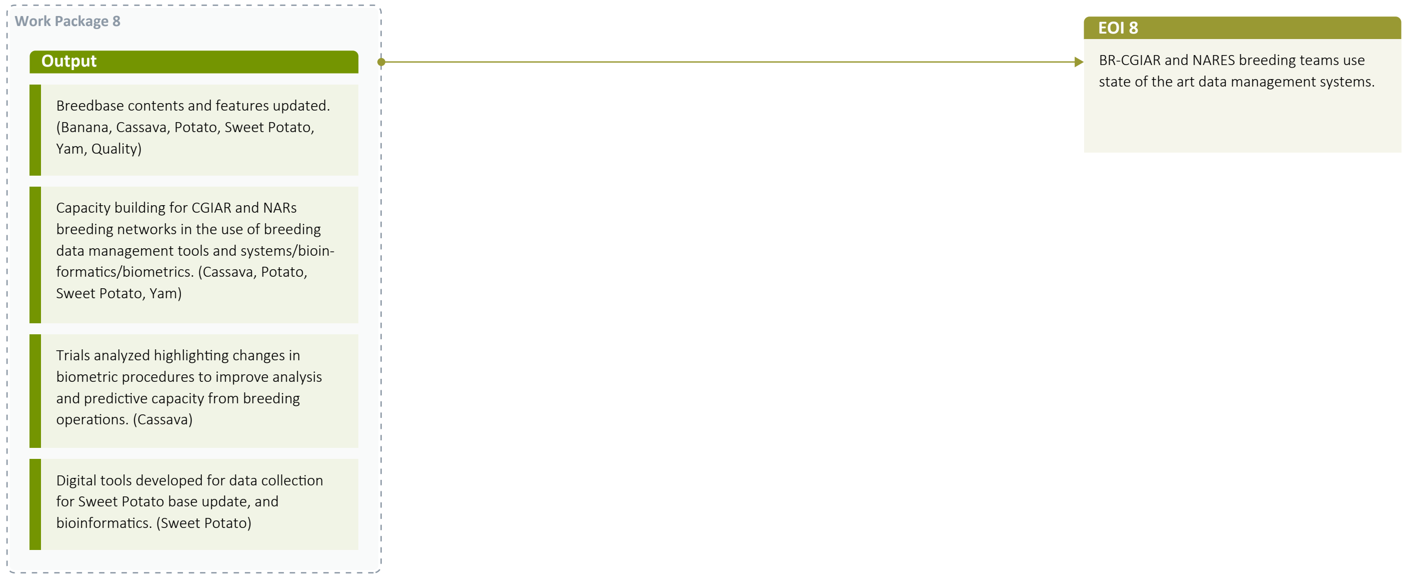
Work Package 7 progress against the theory of change

The ability to conduct standardized, connected operations and proper performance management is oftentimes underappreciated in breeding operations, despite enabling the capture of efficiency gains and significantly reducing breeding expenses. SOPs are being implemented to enhance precision in breeding, resulting in higher success rates, data-driven decision-making to maximize efficiency and minimize costs, and resource optimization so breeding operations are conducted with the utmost efficiency, ultimately leading to significant cost savings. This Work Package collaborates with others to set standards for efficiency, precision, and affordability.

During 2023, all RTB crops developed and adopted diverse SOPs. Extensive costing efforts were conducted in collaboration with the Transform Work Package of the Accelerated Breeding Initiative and crops like yam and cassava have developed a comprehensive cost report for each breeding pipeline. In banana, IITA, NARO and TARI jointly carried out the costing and carefully documented all activities of matooke and mchare banana breeding pipelines, building on a previous major effort to adapt existing costing tools originally designed for annual crops and therefore not fit for purpose to a perennial crop lacking a specific harvest season.

WP8: Smarter use of more data

On track



Work Package 8 progress against the theory of change

Across all CGIAR Centers and their associated national programs, RTB crops rely on BreedBase, a digital ecosystem for modern plant breeding, as a unique and centralized database management system that can smoothly communicate with available digital data collection tools. To keep driving adoption of BreedBase and the corresponding tools by breeding programs, BreedBase contents and features were updated for all crops. For instance, IITA's cassava team uploaded more than 230 phenotyping datasets to CassavaBase in 2023 from its breeding programs.

Thorough capacity building efforts focused on this state-of-the-art database management system, the cassava team trained more than 140 individuals from IITA and many national programs on several topics related to breeding data management, the use of BreedBase and digital data collection tools and biometrics. Similar training was offered by CIP and BTI to potato and sweetpotato breeding teams of CIP and associated national programs. The banana team relies on Musabase to efficiently collect, store, and manage vast amounts of structured and unstructured data through digital data collection methods, ensuring easy accessibility and seamless integration with analytical tools.

Significant progress with the integration of the CliMob platform for the management of citizen science tricot/OFT data into Breedbase was achieved, and templates for participatory variety selection purposes have been harmonized against BreedBase ontologies.

An area of concern is the planned migration of RTB programs to the Enterprise Breeding System (EBS) and whether timing, extensive trainings, and resources will allow that to proceed smoothly without disruption to programs.

Work Package progress rating summary

WORK PACKAGE	PROGRESS RATING & RATIONALE
1	**Progress rating** Throughout 2023, each RTB crop TPPs underwent rigorous review and updating, incorporating country-specific market insights and contributions from key stakeholders.
2	**Progress rating** A stage-gate approach to manage breeding pipelines is being adopted by all RTB crops and is being aligned with the most recent stage-gate guidelines of the Accelerated Breeding Initiative.
3	**Progress rating** Product design teams were organized in banana (Kenya, Tanzania, Uganda), potato (Ethiopia, Rwanda, Kenya), sweetpotato (Uganda, Rwanda), yam (Nigeria, Ghana, Côte d' Ivoire, Benin), and cassava (Nigeria).
4	**Progress rating** Research progress was reported in banana, cassava, and yam in terms of establishing reliable marker-trait associations and translation into low-cost marker assays for high throughput.
5	**Progress rating** All RTB breeding pipelines are implementing activities to reduce breeding cycles and accelerate parent recycling, thus contributing to higher genetic gains.
6	**Progress rating** Progress toward pangenome development in banana and sweetpotato and whole genome long-read capabilities in cassava was observed, as well in the domain of quality/preference traits with high throughput phenotyping tools, hyperspectral imaging for spatial distribution of cassava root constituents, and with machine learning models for quality traits in sweetpotato.
7	**Progress rating** All RTB crops have developed and adopted SOPs. Excellent progress with costing efforts were reported in cassava and yam, and IITA, NARO, and TARI jointly conducted the costing of matooke and mchare banana breeding pipelines.
8	**Progress rating** The contents and several features of BreedBase, RTB crop's centralized database management system, were updated for all crops and extensive training/backstopping was provided, mainly in cassava and sweetpotato.

Definitions

On track

- Annual progress largely aligns with Plan of Results and Budget and Work Package theory of change.
- Can include small deviations/issues/delays/risks that do not jeopardize success of Work Package.

Delayed

- Annual progress slightly falls behind Plan of Results and Budget and Work Package theory of change in key areas.
- Deviations/issues/delays/risks could jeopardize success of Work Package if not managed appropriately.

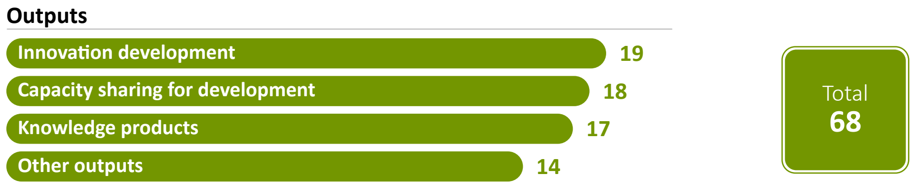
Off track

- Annual progress clearly falls behind Plan of Results and Budget and Work Package theory of change in most/all areas.
- Deviations/issues/delays/risks do jeopardize success of Work Package.

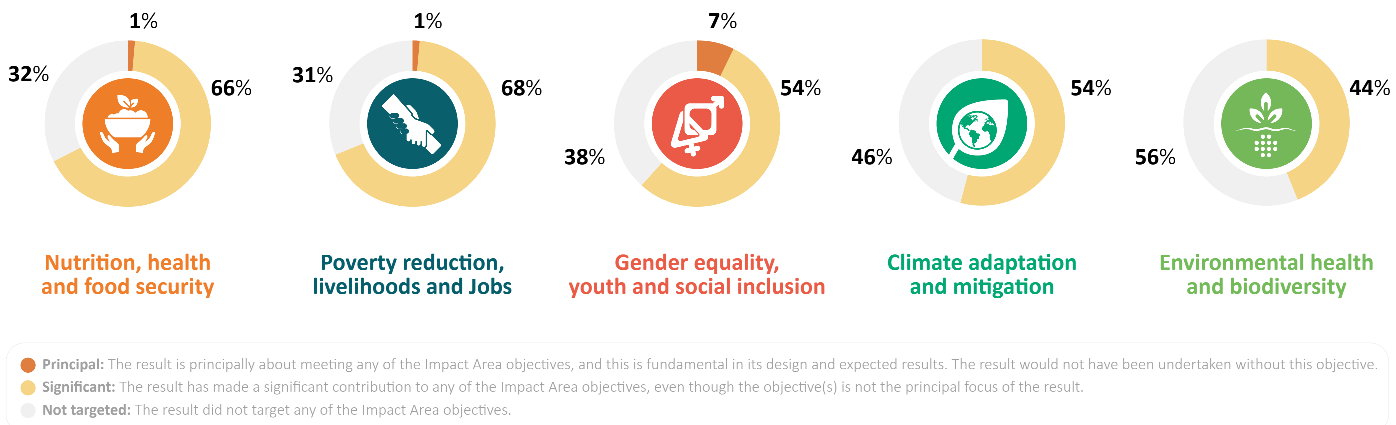
Section 4: **Key results**

This section provides an overview of 2023 results reported by RTB Breeding. These results align with the CGIAR Results Framework and RTB Breeding's theory of change. Source: *Data extracted from the* CGIAR Results Dashboard *on 29 March 2024*.

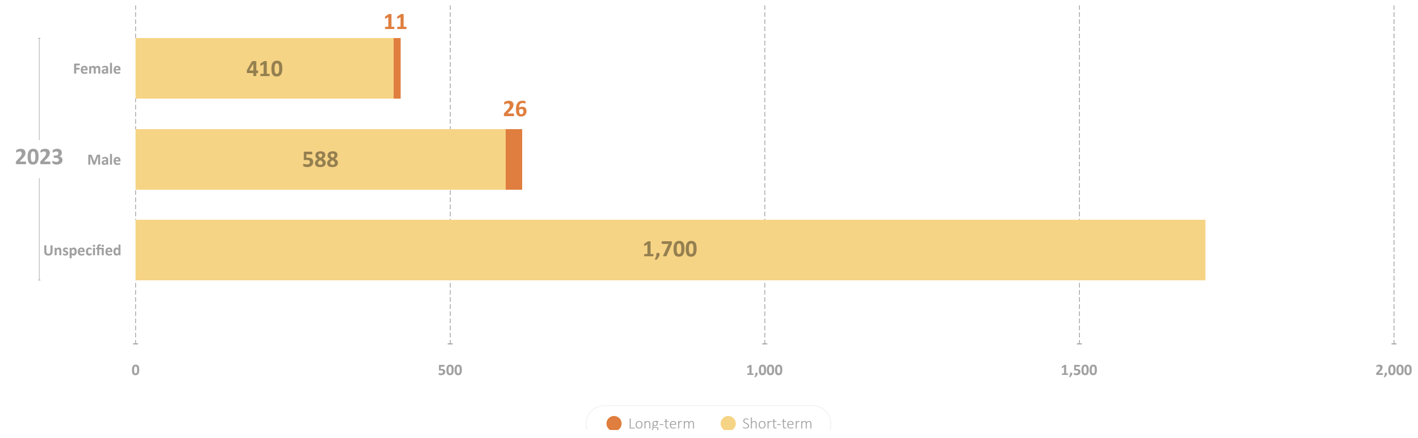
Overview of reported results



Percentage of reported results tagged to CGIAR Impact Areas



Number of individuals trained by RTB Breeding



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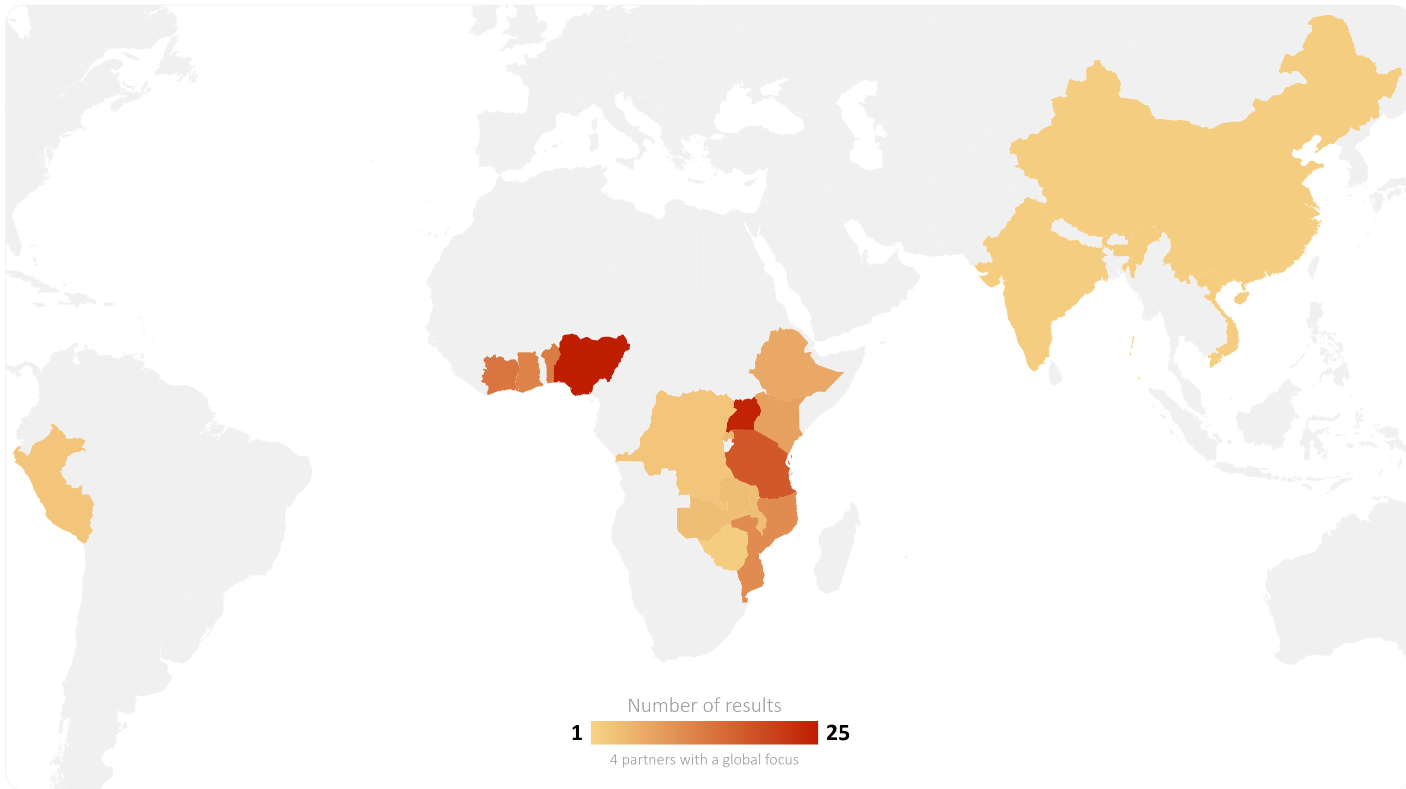
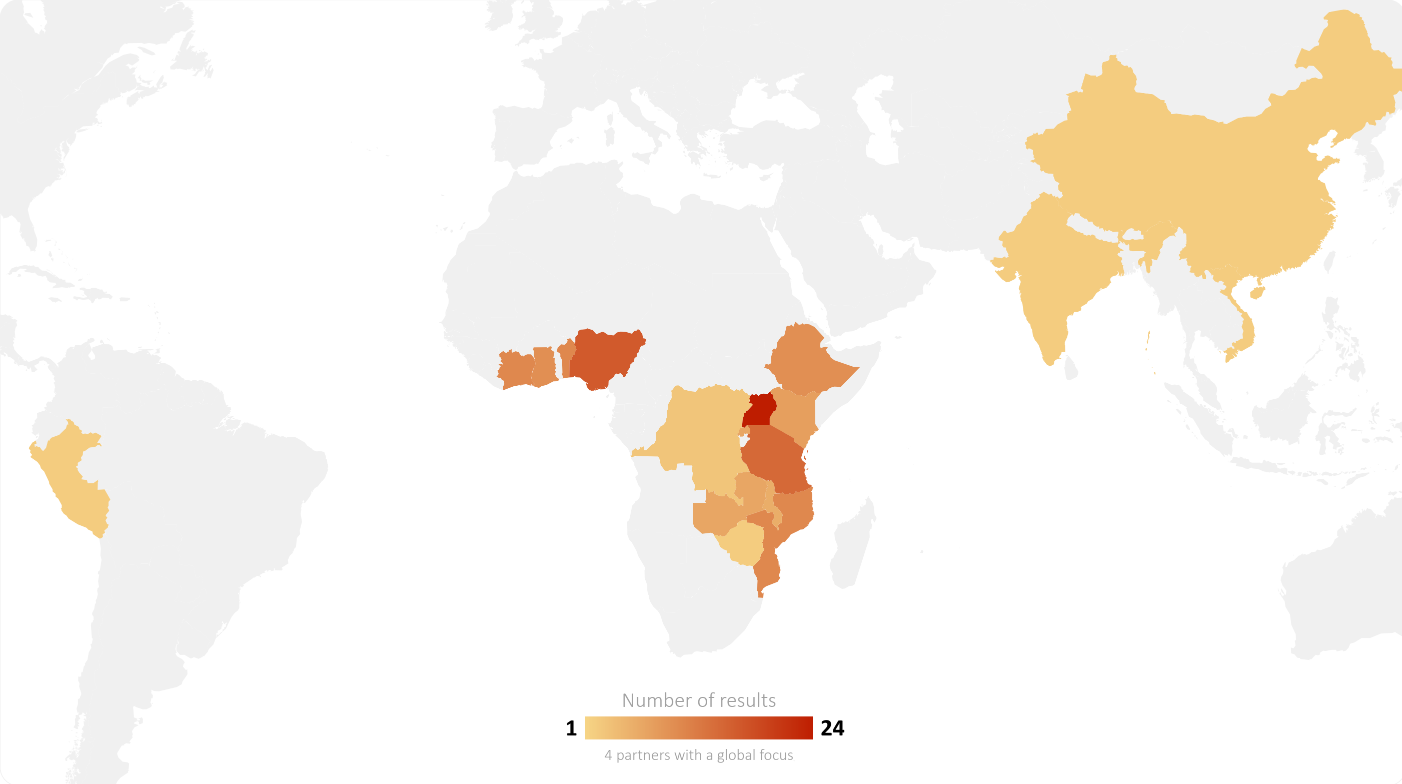
Number of results by country



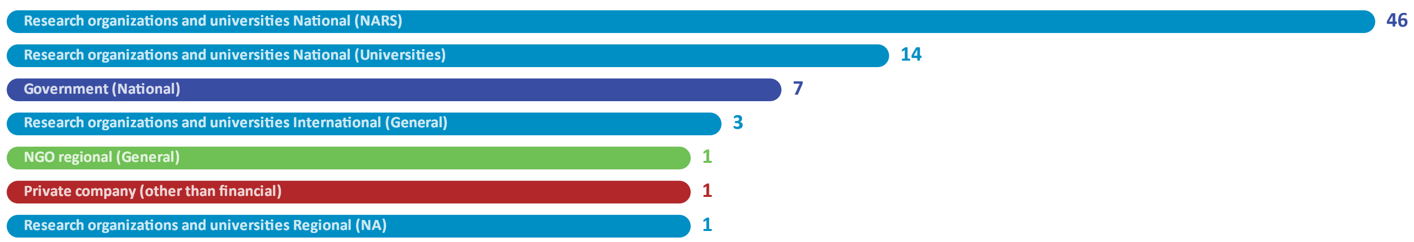
Section 5: **Partnerships**

External partners contributing to results, per country



Colors represent the number of different partners which collaborated on results achieved in a specific country. One result can impact different countries and therefore the same partner can be associated with more than one country. Source: Data extracted from the Results Dashboard on 29 March 2024.

Top 10 partner typologies that contributed to delivering 2023 results



Partnerships and RTB Breeding's impact pathways

The ability of RTB Breeding to build efficient and effective partnerships, particularly with national programs, is one of its comparative advantages. Fifteen such programs from four African regions and more than 11 advanced research institutions across Africa, Europe, and the Americas are involved in this endeavor. Collaborations between CGIAR Centers and partners primarily emphasizes the streamlining of modernized breeding approaches, capacity building, and training young breeders and scientists to enhanced genetic gains delivered on smallholder farmers' fields. Several approaches have been devised to fulfill these objectives, including co-designing TPPs, establishing shared breeding pipeline-specific stage-gates, and developing mechanisms for participation in decision-making regarding the development of market-preferred RTB varieties. The Project's structure ensures that partners contribute to all Work Packages through capacity sharing, innovations, and knowledge products.

In 2023, partners strongly contributed across all Work Packages and result types. Under REFOCUS, TPPs encompassing market segmentation were developed and updated for eight national programs within Eastern, Central and Southern Africa for all crops; this aligns well with the project's objective to co-create products. The stage-gates approach, part of the REORGANISE effort, has been adopted by all RTB crop teams, with standardized roles and disciplines introduced as part of product development. Capacity sharing for development was organized for three national programs, and seven partners contributed to decision rights mapping and defining KPIs for the breeding teams.

TRANSFORM serves as the main vehicle for strengthening CGIAR-NARS breeding networks, with outputs and outcomes aimed at fostering collaboration. Thirteen national programs and two universities participated in capacity sharing for development to establish stronger partnership models and increase contributions to the breeding process. Additionally, two national programs in East Africa contributed to the development of molecular markers for bananas, facilitating the delivery of high-impact traits for breeding programs under DISCOVER. ACCELERATE is the hub for breeding activities in the project, meeting demand for developed varieties desired by value chain actors and delivering genetic gains on farmers' fields. In Nigeria and Uganda, NRCRI and NARO, respectively, conducted farmer trainings and organized field days as part of the DCT network to stimulate demand for improved varieties. In 2023, 17 innovations aimed at delivering demanded varieties were at different stages of development, with 11 national programs and one advanced research institute contributing.

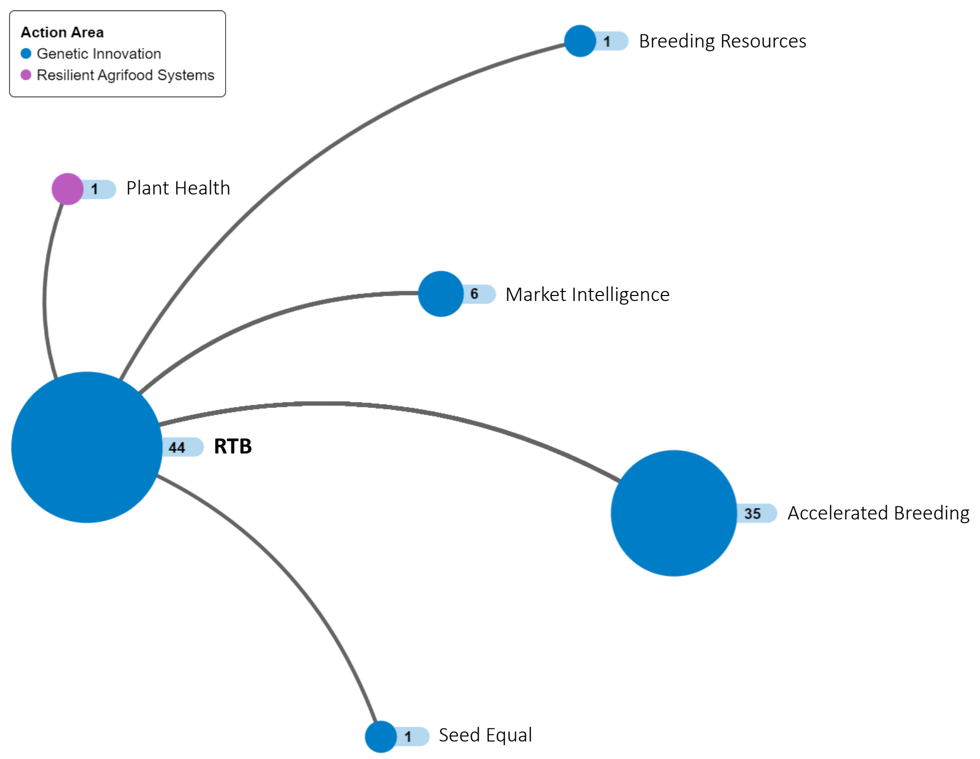
SOPs for breeding pipelines across RTB crops intend to capture efficiency gains and reduce wastage, and establishing the true cost of breeding pipelines will assist in efficiency gains. Seven national programs contributed to SOPs for yam and banana and assessing costs of different breeding stages, leading to up-to-date knowledge and capacities in shared operations.

One example of a partnership orchestrated by RTB Breeding that would otherwise be unlikely is the research collaboration between Uganda's Makerere University and cassava and sweetpotato crop teams to develop machine-learning-based approaches for image-based analysis of root sensory attributes.

Caption: Sweetpotato farmer in Rwanda.
Credit: D. Kiiza (RAB)

Section 6: **CGIAR Portfolio linkages**

RTB Breeding's internal portfolio network



Connections are sized by the number of reported results.

Portfolio linkages and RTB Breeding's impact pathways

Since the remit of RTB Breeding is the genetic improvement of RTB crops, most of our Portfolio linkages take place within the Genetic Innovation Science Group, as shown in Portfolio linkages network graph. The following brief account provides a few examples of connections between RTB Breeding progress and other groups within the CGIAR Portfolio and more specifically with the Accelerated Breeding Initiative.

REFOCUS: A Potato Target Product Profile addresses the needs and preferences of different social groups in East Africa.

REORGANIZE: Blended training developed for national programs in Mozambique, Zambia, Malawi, Tanzania, Uganda, Ethiopia, and Rwanda on sweetpotato germplasm flow for scaling up released varieties.

TRANSFORM: Empowerment of Cassava Farmers and Partners in Breeding and Advancement Choices for Sustainable Agriculture in Nigeria: A Collaborative Decision Platform.

DISCOVER: Marker-trait association identified, developed, and deployed key traits in yam breeding to mainstream best practices in breeding pipelines.

ACCELERATE: Four released matooke hybrids are in vitro multiplied by two small and medium enterprises and two TARI labs, with plants brought to nurseries and given/sold to the public.

These examples demonstrate the coherence of the Project's Portfolio and the logic underpinning the many contact points between RTB Breeding's theory of change and the components of the breeder's equation. These examples also demonstrate how the whole of RTB Breeding is greater than the sum of its parts and how all the Project's individual activities and outputs contribute to its End-of-Project outcomes, and, at a more aggregated level, to specific CGIAR Impact Areas and the UN Sustainable Development Goals.

Due to RTB Breeding's short life cycle of just 22 months, the Project focused in 2023 on instilling a compelling sense of purpose in its staff and partners regarding increasing genetic gains. Our focus on progress made by more than 250 researchers and collaborators toward diverse components of the breeders' equation is most likely to yield a high return on investment and a large impact on the lives of people that RTB Breeding serves.

Section 7: **Adaptive management**

RECOMMENDATION	SUPPORTING RATIONALE
Formalize and implement CGIAR-NARS agreements	The role and multiple contributions of National Programs to RTB Breeding represent a comparative advantage. To further capitalize on it, formal agreements of CG-NARS RTB Breeding networks would provide more clarity in terms of scope, roles, responsibilities, and institutional accountability. An increased ownership of National Programs and an equal peer mindset will not only strengthening their capabilities and ability to achieve impact, but it would also increase RTB Breeding's ability to serve the increasing number of smallholder farmers and city dwellers relying on RTB crops to meet their food security and climate resilience needs.
Establish a common research agenda with the Program for Seed System Innovation for Vegetatively Propagated Crops (PROSSIVA)	To achieve our overall purpose of delivering superior genetic gains in farmers' fields and accelerate the adoption of new varieties, a much closer interaction with seed delivery pathways will be sought. This is particularly mission critical in RTB crops due to the vegetative nature of their propagules. Building on discussions already under way, an ambitious common research agenda needs to be crafted with PROSSIVA to make faster and more targeted progress in key aspects such as early generation seed availability, measuring in cost-effective ways the adoption of RTB improved varieties, and the deployment of traits driving adoption such as gender-related traits, quality/preferences, and shelf-life.
Streamlining genomic selection across all crops	Genomic-selection-based approaches should be the first choice to develop superior advanced lines and to accelerate/improve parent recycling efforts in all RTB crops. This needs to leverage the ability to collect high-quality, relevant phenotyping datasets under high heritability conditions, the development of predictive models customized to the biological and genetic landscape of each RTB crop, and the strengthening of current quantitative genetics capabilities. This would also bring about obvious advantages to current efforts to exploit heterosis and develop hybrid RTB varieties in cassava, potato, and sweetpotato.
Streamline, standardize, simplify, and accelerate the handling and execution of subgrant agreements	A much more expedited processing and execution of subgrant agreements is essential to secure the flow of funding to research partners and to enable work plans to be implemented on time and at the quality agreed upon. Despite good intentions, the ability of some partners to prefinance research activities is limited. In addition, in some cases only one planting window is available each year; any delay in funding disbursements can therefore affect the relevance and/or quality of the phenotypic datasets collected, and thus of advancement, parent recycling and marker-trait associations decisions made.

Section 8: **Key result story**

Lifting genetic gains and increasing impact for smallholder cassava farmers through genomic selection

Yearly genetic gains in cassava have more than trebled in Nigeria, Africa's main cassava producer, with superior varieties now available to smallholder farmers.

Umudike seeds fields at NRCRI, HQ Umudike, Nigeria.
Credit: Chiedozie Egesi (IITA)

Primary Impact Area

Other relevant Impact Areas targeted

Contributing Initiatives

Accelerated Breeding · Breeding Resources · Market Intelligence · Plant Health · Seed Equal

Contributing Centers

CIP · IITA · ABC

Contributing external partners

Bill and Melinda Gates Foundation · 26 partners (NARS, research organizations, Universities)

Geographic scope

West and Central Africa · East and Southern Africa

Although RTB crops are the linchpin of food security in sub-Saharan Africa, the genetic gains made in these crops have been less than that in others. With the embrace of genomic selection, this has recently changed, with a tripling of genetic gains being reported in late-stage field trials of cassava and with superior varieties of this crop already being released in Nigeria. Demand creation trials are helping to speed adoption among Africa's smallholder farmers. RTB Breeding is further accelerating and mainstreaming genomic selection in banana, sweetpotato, and yam.

Cassava is the quintessential African crop and plays a crucial role in food security and resilience for myriad smallholder farmers. Its resilience to heat and drought and tolerance of marginal soils makes it a staple food for over half a billion people worldwide. However, the crop's long crop cycle of 12–36 months, depending on farmers' needs and desires, its low multiplication rate and low seed set per cross, as well as a phenotype-based breeding cycle of 4–6 years, used to represent major bottlenecks to cassava's genetic improvement. Until recently, these challenges hindered the ability of breeders to regularly deliver superior genetic gains, to rapidly respond to emerging biotic and abiotic constraints, and to sustain the sustainable expansion of this remarkable crop into harsher marginal environments.

One CGIAR Centers and national breeding programs have embraced advances in genomics that have already revolutionized plant breeding in other crops, making tens of thousands of SNP markers available and affordable. These advancements underpin genomic selection, namely the ability to predict the performance of untested genotypes, thus facilitating the selection of parents with superior genetic merit and the identification of clones with superior performance. This step change in cassava breeding enables transitioning to predictive breeding that delivers enhanced efficiency and genetic gain.

Continuous deployment of genomic selection and refinement of prediction models has not only produced unprecedented annual genetic gains of up to 2–3 percent for dry yield but also cut cassava's breeding cycle in half. Above all, the first release of new varieties of the crop by market segment has occurred in Nigeria. Building on this success, the first phase of RTB Breeding is further mainstreaming genomic selection through a close-knit partnership of scientific talents from IITA, the Alliance of Bioversity and CIAT, and several national programs such as NaCRRI (Uganda), NRCRI (Nigeria), TARI (Tanzania) in Africa and the Brazilian Agricultural Research Corporation (Embrapa) in Brazil. The power of genomic selection is being further enhanced by the steady expansion of on-farm testing through tricot as well as updates of CassavaBase, an open-access, multifunctional breeding database for efficient management of massive amounts of phenotype and genotype data points (https://cassavabase.org), and use of plant growth regulators, pruning of young branches, and LED lighting to induce flowering and enhance seed set.

Although cassava was the RTB crop first enhanced by genomic selection, other RTB crops are quickly catching up. For instance, yam breeders at IITA and NRCRI have combined genomic selection with novel propagation techniques to hasten parental recycling and reduce breeding cycles. All of these represent significant changes in several components of the breeder's equation.

It is perhaps in polyploid RTB crops where genomic selection is most impactful. Banana breeders are exploiting it for faster parental recycling, hence decreasing breeding cycles in diploid, tetraploid, and tetraploid by diploid parental combinations. First results of collaborations between IITA and NARO breeders in Uganda are encouraging, with prediction accuracies in the 0.67–0.71 range observed for yield components in matooke. In sweetpotato, CIP scientists working with colleagues from NaCRRI and IIAM have progressed to the second cycle of population training.

> The small RTB breeding community was an early adopter of "breeding modernization" tools. Their market research defined product profiles that meet consumer needs. The combined impact has been dramatically accelerated genetic gain providing higher yielding varieties with high consumer ratings. RTB crops are entering their 'Green Revolution' moment
>
> Jim Lorenzen, Senior Program Officer, Bill & Melinda Gates Foundation

Front cover photo

Banana: Female farmer receiving suckers of matooke in Tanzania. Credit: Rony Swennen (IITA)
Cassava: Cassava harvest in Nigeria. Credit: Chiedozie Egesi (IITA)
Potato: Potato crop management in Kenya. Credit:Thiago Mendes (CIP)
Sweetpotato: Sweetpotato harvest in Malawi. Credit: Stanley Kwendani (DARS)
Yam: Yam harvest in Nigeria. Credit: Asrat Amele (IITA)

Back cover photo

Semi Autotrophic Hydroponics
Yam multiplication.
Credit: Asrat Amele (IITA)

CGIAR