The **Jewels** of ICRISAT

ICRISAT
Science with a human face

International Crops Research Institute for the Semi-Arid Tropics

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1972-2012 ICRISAT

About **ICRISAT**

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) is a non-profit, non-political organization that conducts agricultural research for development in Asia and sub-Saharan Africa with a wide array of partners throughout the world. Covering 6.5 million square kilometers of land in 55 countries, the semi-arid tropics have over 2 billion people, and 644 million of these are the poorest of the poor. ICRISAT and its partners help empower these poor people to overcome poverty, hunger and a degraded environment through better agriculture.

ICRISAT is headquartered in Hyderabad, Andhra Pradesh, India, with two regional hubs and five country offices in sub-Saharan Africa. It is a member of the CGIAR Consortium.

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Foreword from the Director General

The year 2012 marks a significant milestone in the institutional life of ICRISAT as we celebrate our 40th anniversary. This publication is therefore a timely chronicle of the Institute's work and impacts over our four decades of service to the poor people of the dryland tropics.

The book takes up an idea suggested by our Governing Board to highlight the 'jewels' of ICRISAT – the 16 breakthroughs and innovations described in this publication. These stories revolve around and cut across our four research programs: resilient dryland systems; markets, institutions and policies; grain legumes; and dryland cereals.

ICRISAT's target area – the dryland tropics – is home to more than 800 million people. These include the world's poorest people, spread across 55 developing countries in Asia and sub-Saharan Africa. The dryland tropics are characterized by erratic rainfall, degraded soils and biodiversity, water scarcity, droughts, floods, and very poor physical and social infrastructure. People of the drylands are perennially plagued by poverty, hunger, food and nutritional insecurity, and powerlessness. The confluence of global warming, droughts, floods, increasing land degradation, rising food prices, soaring energy demand and population explosion is leading to a perfect storm that is inflicting untold suffering on millions of farming communities all over the world. Being the only global research center with a mandate focused on serving the dryland tropics, ICRISAT and our partners seek to help end this chronic plague.

This publication aims primarily to help the reader understand ICRISAT's core science and our impact in overcoming the daunting challenges of the dryland tropics. Likewise it illustrates the ways in which science can be mobilized to help achieve six critical development outcomes needed to bring about inclusive market-oriented development: food sufficiency, intensification,

diversification, resilience, health and nutrition, and the empowerment of women.

Over four decades, ICRISAT's innovations in these areas have greatly improved rural livelihoods, contributing to the CGIAR's high return of $17 for each dollar invested. Our strategic public, private and civil society partners worldwide are essential to this impact.

Moving forward on the threshold of our fifth decade, we have fine-tuned our strategic direction to respond to the rapidly changing environment, and in particular to the emergence of a new CGIAR. Toward this end, ICRISAT has embraced inclusive market-oriented development, as a pathway to end poverty, and not just alleviate it.

This development paradigm aims to unlock the untapped potential of the dryland poor, empowering them with more productive and resilient innovations, supportive policies, and diverse, purposeful, and action-oriented partnerships.

Enhancing our impacts and affirming our relevance, ICRISAT is actively advancing research on emerging global issues including climate change and vulnerability, drought and land degradation, biofuels, agricultural diversification, and linking farmers with markets.

Apart from the 16 'jewels' featured in this publication, ICRISAT is surging ahead with our partners to generate and share cutting edge global scientific innovations, to bring about genuine pro-poor growth and inclusive market-oriented development. We would like to thank our donors and partners for their unwavering support in helping us pursue this pathway to lasting prosperity in the dryland tropics of the world.

William D. Dar

Abbreviations and acronyms

AGRA	Alliance for a Green Revolution in Africa
ARI	advanced research institute
CCSHAU	CCS Haryana Agricultural University
cELISA	competitive enzyme-linked immunosorbent assay
CGIAR	CGIAR is a global research partnership for a food secure future
CMS	cytoplasmic-nuclear male-sterility
DM	downy mildew
ESA	eastern and southern Africa
FAO	Food and Agriculture Organization of the United Nations
GMS	genetic-male sterility
HPLC	high performance liquid chromatography
HPRC	Hybrid Parents Research Consortium
ICAR	Indian Council of Agricultural Research
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IER	The Malian Institut d'Economie Rurale
INERA	Institut National de l'Environnement et des Recherches Agricoles, Burkina Faso
IPG	international public good
KARI	Kenya Agricultural Research Institute
NARS	national agricultural research system
NASFAM	National Smallholder Farmers' Association of Malawi
QTL	quantitative trait loci
SARI	Selian Agricultural Research Institute
SINGER	System-Wide Information Network for Genetic Resources
SSR	simple sequence repeat
USA	United States of America
USAID	United States Agency for International Development
WCA	West and Central Africa

The **jewels** at a glance

Community-based integrated watershed management

A community-based approach to integrated rural development uses watershed management as an entry point.

Fertilizer microdosing

Small doses of fertilizer applied in the right place at the right time, combined with an inventory credit system (warrantage), lead to large benefits in yields and incomes in several countries in sub-Saharan Africa.

Village Level Studies

ICRISAT's contribution to the global knowledge base on rural households helps identify constraints and pathways to agricultural development in the dryland tropics.

Aflatoxin testing kit

An inexpensive innovation helps identify aflatoxin-free grains to meet international market standards and ensure higher returns for farmers, and provide safer products for consumers.

Drought-tolerant groundnut

An ICRISAT groundnut variety resists drought and diseases, has good fodder quality and replaces varieties grown for more than 60 years, bringing hope to millions of poor farmers.

Early maturing chickpea

Early maturing chickpea, with improved fusarium wilt resistance, high yield potential and good seed quality, has greatly increased crop area and productivity in short-season environments by avoiding terminal drought and heat stress.

Hybrid pigeonpea

Cytoplasmic-nuclear male-sterility-based pigeonpea hybrids yield up to 40% more than conventional cultivars.

Pigeonpea in eastern and southern Africa

ICRISAT varieties resist wilt, have high yields and large seeds, and are widely grown in Kenya, Malawi, Mozambique, Tanzania and Uganda, increasing farmers' incomes by up to 80%.

Pigeonpea genome

Pigeonpea is the first 'orphan crop', the first 'non-industrial crop' and the second food legume with a completed genome sequence.

Guinea-race sorghum hybrids

Sharing the benefits of hybrid vigor with West African farmers, while retaining the adaptation and quality traits of local germplasm.

Extra-early pearl millet hybrid

Inter-institutional collaboration integrates conventional, participatory and marker-assisted breeding methods to develop extra-early pearl millet hybrid HHB 67 Improved, which has enhanced downy mildew resistance and yield.

Sweet sorghum

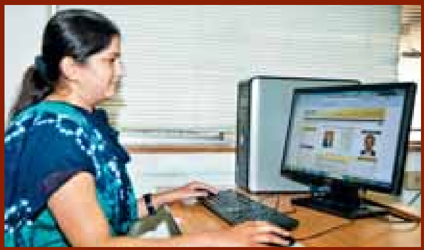
A smart, multipurpose (food, feed, fodder, fiber and fuel) crop adapted to drought and climate change provides higher incomes for farmers.

Genetic resources for food security

ICRISAT's genebank conserves more than 120,000 accessions and supports the global crop improvement community to develop improved cultivars.

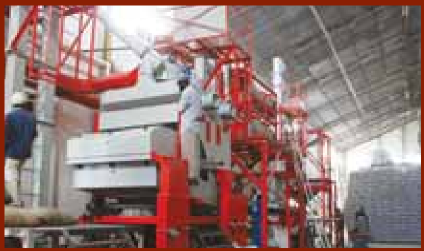
Hybrid Parents Research Consortium

Public–private partnerships produce scientific innovations and products for the poor.



Open access repository

An interoperable open access institutional repository for ICRISAT knowledge products



Seed systems in sub-Saharan Africa

Facilitating access by poor farmers to seeds of ICRISAT's improved varieties in sub-Saharan Africa.


Community watersheds are lifesavers in the harsh environments of the semi-arid tropics

Community-based integrated **watershed management**

A community-based approach to integrated rural development uses watershed management as an entry point

Improved access to water means more than just survival in the dryland tropics. In these poverty hot spots, agriculture is a major challenge for smallholder farmers, with a scarce water supply compounded by degraded natural resources and low crop yields.

Drawing on 35 years of research, ICRISAT and its partners have developed a model of community-based watershed management consortia that bring together institutions from public sector research, civil society and farming communities to share their knowledge in an equitable and efficient manner, and implement multidisciplinary activities at a landscape level.

The innovation

At the heart of this innovation is a participatory model, involving a consortium of partners from the Government of India (Central Research Institute for Dryland Agriculture, part of the Indian Council for Agricultural Research [ICAR], Government of Andhra Pradesh, and the National Remote Sensing Centre) civil society organizations and private companies. The consortium works with ICRISAT and watershed communities to manage soil and water resources and establish livelihood enterprises at the village level. This model was started in India and scaled out in China, Thailand and Vietnam.

Recognizing and building on social capital in rural communities has been a key intervention in addressing rural poverty. Adarsha watershed at Kothapally in Andhra Pradesh, India is a classic example. Today, Kothapally is a prosperous village on the path to long-term sustainability and has become a beacon for science-based rural development. Two major factors have contributed to this development: (i) the increased cropping intensity using high value crops, including vegetables; and (ii) the increased productivity of rainfed crops as a result of enhanced water availability.

During the hard drought of 2002, people's incomes in Kothapally were buffered by enterprise diversification that was supported by the community-based watershed interventions. Similarly, between 2000 and 2003 in Powerguda, another exemplar village in Andhra Pradesh, investments in new livelihood enterprises, such as a seed oil mill, tree nurseries, and vermicomposting increased average incomes by 77%.

Better crop–livestock integration offers a tool for poverty reduction. Inhabitants of the Lucheba watershed in Guizhou Province of China have transformed their economy by improving their roads and water supply. With technical support from the consortium, the farming system was intensified and diversified away from rice and rapeseed, toward livestock and horticultural crops. Forage production (using wild buckwheat as an alley crop) has controlled erosion, provided feed for pigs and increased farm income from sloping lands.

Efficient management of rainwater through *in-situ* conservation has improved water availability in the watersheds. Meanwhile, the establishment of water harvesting structures has also improved groundwater levels. In Bundi, Rajasthan, for example, water levels in the wells were enhanced by an increased groundwater recharge of 5.7 m, which permitted an expansion in the irrigated area from 207 to 343 hectares.

Community-based integrated watershed management has resulted in a two-pronged achievement:
i) protecting the environment; and ii) sustaining development. The effectiveness of improved watershed management technologies was evident in all the sites in India, China, Thailand and Vietnam. This is particularly significant on sloping topography; for instance, in Tad Fa, Thailand, interventions such as contour cultivation, vegetative bunds and fruit trees grown on steep slopes reduced seasonal runoff to less than half (194 mm) and soil loss to less than one seventh (4.2 t ha^{-1}) of those seen under the conventional system.

In addition to experiencing low productivity, a large majority of the drylands are severely deficient in micronutrients (zinc, boron and sulphur). The

Enhancing partnerships and institutional innovations through the consortium approach has proved to be a major impetus for harnessing the potential of watersheds to reduce household poverty

Microenterprises such as vermicomposting are part of the watershed program and provide income opportunities for women

application of fertilizers to correct this deficiency increased crop yields by up to 70% over farmers' practices. Similarly, the introduction of integrated pest management decreased the use of pesticides by 50–60%.

Increased carbon sequestration, amounting to 7.4 t ha^{-1} in 24 years, was observed with improved management practices in a long-term watershed experiment at ICRISAT-Patancheru, India. In partnership with ICAR, carbon sequestering systems and management practices were subsequently identified.

Using participatory research techniques, biodiversity conservation practices were also promoted in the watersheds. Pronounced agro-biodiversity impacts were observed in the Kothapally watershed, where farmers now grow 22 crops in a season, as a result of a shift in cropping pattern away from cotton (which dropped from 200 ha in 1998 to 100 ha in 2002) to a maize/pigeonpea intercrop system (which increased from 40 ha in 1998 to 180 ha in 2002). The rehabilitation of degraded common lands in the Bundi watershed in Rajasthan through community participation not only made the village self-sufficient in fodder, but also generated additional income for the community through the sale of excess fodder.

Enhancing partnerships and institutional innovations through the consortium approach has proved to be a major impetus for harnessing the potential of watersheds to reduce household poverty. Complex issues were addressed effectively by the joint efforts of ICRISAT and its key partners – national agricultural research systems (NARS), non-governmental organizations, local government agencies, agricultural universities and

Intensification of cropping and diversification with high-value crops then follows. Through enhanced community participation, even the most vulnerable groups (generally women and the landless poor) have been empowered and trained.

The Comprehensive Assessment of the impacts of watershed programs in India has provided evidence of their economic viability with a benefit/cost ratio of 2:1 and an internal rate of return of 27%. Watersheds show a two–three fold increase in productivity, and a 51% increase in cropping intensity, as well as reduced runoff (45% lower) and soil loss (1.1 t ha^{-1} lower) compared to the situation prior to the intervention. The community-based watershed management process and consortium model have helped to bring together relevant government agricultural programs around watersheds, promoted rainwater harvesting, restored artificial water bodies, and led to widespread soil testing for micronutrients.

Ex-ante impact assessment studies for Andhra Pradesh's Rural Livelihoods Program in five districts with improved watershed management revealed impressive returns of $608 million over 10 years for four major crops (sorghum, groundnut, pigeonpea and maize).

In Thailand, the model has fostered better working relations with research and development institutions and has contributed to stronger policy and planning to ensure that every farm household has access to a pond. Similarly, changes in the mindset of policy makers in Vietnam, China and India have led to the scaling out of a number of new research for development projects in many rainfed areas.

ICRISAT and its partners' active involvement in the Comprehensive Assessment of Water Management in Agriculture has ensured a greater emphasis on the efficient use of water in rainfed agriculture at the global level, and has changed the lives of at least 20 million people in Asia.

other private interest groups – while retaining farm households as the key decision makers of substantive change.

The impact

The consortium model has helped to unlock the potential of rainfed agriculture and ensured improved productivity through the sustainable intensification of rainfed systems. Partnerships have improved rural livelihoods through science-based development and results have been scaled up, demonstrating the power of collective action and agricultural innovation.

Fertilizer **microdosing**

Small doses of fertilizer applied in the right place at the right time, combined with an inventory credit system (warrantage), lead to large benefits in yields and incomes in several countries in sub-Saharan Africa

Land degradation affects more than half of Africa, leading to estimated losses of $42 billion in income and 5 million hectares of productive land each year. Crop yields are low as a result of poor farming techniques, nutrient deficiency and lack of water, particularly in sub-Saharan Africa. Farmers are unable to invest in fertilizer, triggering a cycle of soil nutrient depletion, low productivity and hunger.

Unable to feed their families, farmers abandon unproductive land to clear forests and plow new

A little fertilizer goes a long way in improving plant resilience

areas. Clearing new lands for farming accounts for an estimated 70% of the deforestation in sub-Saharan Africa.

The innovation

Microdosing involves the application of small, affordable quantities of inorganic fertilizer with the seed at planting time, or as a top dressing three to four weeks after emergence. This enhances fertilizer efficiency compared to spreading fertilizer over the field.

Farmers who use microdosing apply 2–6 gram doses – about a full bottle cap or a three-finger pinch – of compound fertilizer (diammonium phosphate (DAP) or NPK) in the hole where the seed is placed at the time of planting. This is equivalent to about 20–60 kg of fertilizer per hectare of land.

This technique uses only about one tenth of the amount typically used on wheat, and one twentieth of that used on maize in the USA. Yet in sub-Saharan Africa, crops are so starved of nutrients such as phosphorous, potassium and nitrogen that even this micro amount often doubles crop yields.

Where soil is hard, farmers may dig small holes or planting basins (known as *zaï* in West Africa) before the rains start and fill them with manure, if available. When the rains begin, they put fertilizer and seeds in the hole and the soil provides a moist environment encouraging root growth. Water is captured instead of running off the hard-crusted soil.

By correcting soil deficiencies for essential nutrients with tiny doses of fertilizer, root systems develop and capture more water, increasing yields and ensuring plants are less prone to drought.

ICRISAT and its partners are testing two market development strategies to address capital constraints.

Poor farmers often encounter difficulties storing their grain, transporting it to market and satisfying their financial needs at harvest time. They are forced to sell to middlemen immediately post-harvest when supply is abundant and prices are low. Farmers are caught in a vicious circle as they are under pressure from merchants to repay loans taken to eke out a living during the hardship period between May and July, and to invest in their farms.

In West Africa, the 'warrantage' or inventory credit approach is a welcome solution to farmers' capital constraints. Farmers place part of their harvest in a local storehouse in return for inventory credit. This allows them to meet pressing post-harvest expenses and engage in dry season income generating activities, such as sheep fattening, vegetable cultivation using small scale (drip) irrigation, groundnut oil extraction and small trading. The stored grain may be sold later in the year at a much higher price, when farmers can make a good profit.

Moreover, this cooperative approach trains farmers to work together to protect stored grains from insects and also helps them to buy fertilizer in bulk and repackage it in smaller, more affordable units through local input stores. Hundreds of farmer organizations in the region now use the warrantage system, which links them directly not only to markets but also to financial institutions.

The impact

Fertilizer microdosing can contribute to ending widespread hunger in drought-prone areas of Africa. It has reintroduced fertilizer use in Zimbabwe, Mozambique and South Africa. In West Africa, as a result of previous ICRISAT projects, some 25,000 smallholder farmers in Mali, Burkina Faso and Niger have learned the technique and experienced increases in sorghum and millet yields of 44 to 120%, along with an increase in their

By correcting soil deficiencies for essential nutrients with tiny doses of fertilizer, root systems develop and capture more water, increasing yields and ensuring plants are less prone to drought family incomes of 50 to 130%. A regional project of the Alliance for a Green Revolution in Africa (AGRA) is targeting 360,000 households with the microdosing technology by the end of 2012.

In Zimbabwe, despite poorer than average rains, microdosing increased grain yields, enabling about 170,000 households to increase cereal production by an estimated 40,000 tons. The ICRISAT-supported program significantly improved household food security and saved $7 million in food imports. Many of these farmers became interested in investing their own resources in fertilizer, but access has remained a constraint. The program has started working with fertilizer companies to test strategies for resolving this problem, through improved access to affordable smaller packs of fertilizer.

Although results have shown consistent yield increases, farmers have reported that microdosing is time consuming and laborious and that it is difficult to ensure each plant gets the right dose of fertilizer. In an attempt to address these issues, researchers are looking at packaging the correct dose of fertilizer as a tablet that aids application, and this is proving to be popular. In collaboration with partners in national agricultural research systems, ICRISAT is also exploring the use of seed coating and an animal-drawn mechanized planter as other options to further reduce the quantity of fertilizer used, as well as to address the labor constraint.

Lack of access to fertilizer and credit, insufficient flows of information, inadequate training for farmers and inappropriate policies have been identified as major constraints to the widespread adoption of the technology in sub-Saharan Africa. Greater adoption of microdosing requires supportive and complementary institutional innovations, as well as input and output market linkages.

A microdose of fertilizer with the seeds in the planting hole gives the plant a healthy headstart

Working with the Food and Agriculture Organization (FAO), local agricultural centers, and a network of international donors and partners – including the West and Central African Council for Agricultural Research and Development, the United States Agency for International Development (USAID) and AGRA – ICRISAT hopes to increase the number of farmers using microdosing and the warrantage system from 25,000 to 500,000 in the next few years. This will go a long way toward alleviating food scarcity and hunger in the semi-arid tropical regions.

Village Level Studies

ICRISAT's contribution to the global knowledge base on rural households helps identify constraints and pathways to agricultural development in the dryland tropics

Too often, the voices of the poor are muted and do not resonate in agricultural statistics and policy decisions because reliable and timely data on the consequences of change for the rural poor are not available. Understanding village and household dynamics, the economic, social, political and institutional drivers affecting rural household welfare, and the role of women and men in agriculture is at the core of research for development.

Despite its importance, there is surprisingly little micro-level quantitative and qualitative evidence on the long-term changes affecting the development pathways of rural agrarian households.

The ICRISAT Village Level Studies were initiated to enhance the availability of reliable household, individual and field-specific, high-frequency time-series data in purposively selected villages in the semi-arid and humid tropics of South Asia. They provide an understanding of farming systems in rural areas and identify the socioeconomic constraints faced by farming communities.

ICRISAT began its Village Level Studies with two villages in each of three regions in the semi-arid tropics of peninsular India in 1975. In one village in each region, panel data collection continued until 1984–1985. In the early 1980s, Village Level Studies were also undertaken in six villages in Burkina Faso and four villages in Niger in West Africa. ICRISAT's Village Level Studies are one of the first major panel surveys in the world to use a household framework in a developing country.

The early 2000s saw the revival of the Village Level Studies in South Asia, which later expanded from

Social scientists interacting with farmers in Niger

six villages in two states in India, to 42 villages encompassing five states in semi-arid tropical India, three states in East India, and 12 districts in Bangladesh, in partnership with the International Rice Research Institute, the National Centre for Agricultural Economics and Policy Research of India and state agricultural universities.

The innovation

The Village Level Studies data bank is equivalent to the 'genebanks' of biological scientists. It provides the testing ground for innovations in social science and new ICRISAT technologies. With its unique high-frequency longitudinal household panel data, the Village Level Studies dataset is now an extremely valuable international public good.

The Village Level Studies provide a 'community-based laboratory' in which to undertake detailed research on a variety of topics as the need arises. They are multidisciplinary in nature, integrating biological, technical, social and economic approaches. They produce exceptionally high quality data from continuous engagement, and facilitate the study of seasonality and the intensive scrutiny of social networks. The Village Level Studies dataset helps us ask what has happened to households and individuals, in terms of their incomes, consumption patterns and expenditures, social and institutional structures and arrangements, human capital, adaptive capacities and responses to policy change. The studies also facilitate the measurement of agricultural income and consumption risks, and therefore permit the evaluation of production, consumption, investment, agricultural and social behaviors under risk.

The Village Level Studies capture shocks that affect household welfare over a long period of time and thus establish a basis for assessing adjustments to specific sources of risk. They enable social scientists to trace seasonal, annual and long-term changes in well-being, supporting the study of the dynamics of poverty and wealth acquisition. They also permit the study of the pathways by which new technologies, markets, institutions, policies and programs have an impact on poverty, village economies and societies.

Finally, the Village Level Studies facilitate understanding development pathways and transformation process of village economies over time and across villages.

With its unique high-frequency longitudinal household panel data, the Village Level Studies dataset is now an extremely valuable international public good

The impact

Village Level Studies were initially designed to help ICRISAT set its research priorities by providing insights into the socioeconomic and agro-biological conditions of marginal environments. ICRISAT's Socio-economics Research Program undertook extensive research on rural livelihoods in the dryland tropics to understand poverty, risks and vulnerability, coping mechanisms and livelihood options. These findings stimulated policy makers and development practitioners to formulate programs that were appropriate to the actual situation.

This single dataset reveals many valuable insights, and was even described as the 'goose that lays the golden eggs' in one of the World Bank's World Development Reports. Village Level Studies are arguably the single most valuable contribution of the CGIAR system to understanding the socioeconomic situation in developing countries and its relationship to technology adoption, particularly for smallholder farmers in marginal environments. It has been noted in the literature that it is difficult to identify any other development economics dataset that has been as influential as the Village Level Studies since 1975. Indeed, much information about the microeconomics of development in the dryland tropics is derived from the Village Level Studies core dataset.

An inventory of publications reveals that more than 150 papers and three dozen doctoral dissertations have been based on the empirical analysis of Village Level Studies data in the dryland tropics of India and West Africa. A recent search in Google Scholar shows that this body of work has generated over 10,000 citations.

C Bantilan (in white), Research Program Director- Markets, Institutions and Policies, and team members discuss collective action by women with farmers in Kanzara Village, Maharashtra state, India

These rigorous scientific studies have addressed a wide range of issues such as household decision making, coping mechanisms, risk attitudes, technical efficiencies, nutrition and health, gender, technology adoption, rural labor and financial markets, poverty alleviation and common property resources.

Research papers based on the Village Level Studies have appeared in a wide range of highly reputable international and national journals, highlighting the broad-based appeal of the dataset to the scientific community. The Village Level Studies provide the only dataset in the world that has been analyzed so extensively by the scientific community and, as a result, new policies and technologies have been developed to suit the dryland tropics. It combines a rich historical database with ICRISAT's unmatched expertise in long-term surveys.

Aflatoxin testing kit

An inexpensive innovation helps identify aflatoxin-free grains to meet international market standards and ensure higher returns for farmers, and provide safer products for consumers

Agricultural products are often invaded by fungi that can produce poisonous substances called mycotoxins. Among mycotoxins, aflatoxins produced by *Aspergillus flavus* and *A. parasiticus*, occur globally. Aflatoxin B1 is the most prevalent and toxic form within this group of closely related compounds.

Groundnuts (peanuts), maize, sorghum, pearl millet, chilies, pistachios, cassava and other agricultural crops are regularly contaminated by aflatoxins, affecting human and livestock health, and reducing the marketability of food products. Aflatoxin contamination is invisible and more than 5 billion people in developing countries are constantly and unknowingly exposed to it by consuming affected foods.

Consumption of aflatoxins by humans can lead to acute hepatitis, immune suppression and hepatocellular carcinoma. Acute aflatoxin intoxication can even result in death. A person's chances of contracting liver cancer are compounded significantly where aflatoxins and hepatitis B virus occur together, conditions that affect an estimated 20 million people in India. Children exposed to aflatoxins suffer from poor growth and immune suppression, making them susceptible to several immuno-suppressive disorders.

The results obtained are comparable to the highly sensitive HPLC technology. The kit has drastically reduced the cost of testing crops and can be used with minimal laboratory facilities. A further important advantage of this technology is that most of the required chemicals are locally available in developing countries.

As a result of these dangers, many countries reject imports of agricultural products that exceed certain levels of aflatoxin, costing developing-country farmers millions of dollars each year in lost sales.

The innovation

The key to defeating this invisible killer lies in efficient and inexpensive detection. While developed countries use technologies such as high performance liquid chromatography (HPLC), high performance thin layer chromatography, thin layer chromatography and antibody-based assays to monitor aflatoxins in food and feed commodities, these are expensive for routine quantitative estimation. Moreover, they require laborious, time consuming and extensive sample cleanup operations, which deter developing countries from using them. The high cost of aflatoxin estimation has also constrained the development of new resistant varieties and integrated crop management technologies.

In the face of such challenges, ICRISAT scientists devised a simple and affordable test kit using polyclonal and monoclonal antibodies developed in-house. The test uses a competitive enzyme-linked immunosorbent assay (cELISA) to rapidly detect the presence of aflatoxins.

The impact

The cELISA test has provided a unique opportunity for ICRISAT and its partners to conduct field studies to select breeding lines, develop pre- and post-harvest management technologies and discover dietary sources of aflatoxins. This has stimulated interventions that enhance food safety, human health, trade and ultimately farmers' incomes.

Responding to the increasing demand for cost-effective testing facilities, ICRISAT helped set up aflatoxin monitoring laboratories in India, Kenya, Malawi, Mali and Mozambique, where the cELISA technology is used. Local personnel were trained to manage the facilities. The diagnostic reagents are widely distributed to partners in Asia and sub-Saharan Africa. These laboratories contribute to quality certification of farmers' produce and enhance the competitiveness of their produce in domestic and international markets.

The kits are now being used in around 20 laboratories across the world. In India, several commercial food and feed companies have used the kit with great success. Malawi saw its status as a major groundnut exporter eroded by aflatoxin outbreaks in the 1970s. Over the past five years, the National Smallholder Farmers' Association of Malawi (NASFAM) has successfully used the new technology, in conjunction with HPLC, as part of a broader effort to regain its once-lucrative European export market.

Drought-tolerant **groundnut**

An ICRISAT groundnut variety resists drought and diseases, has good fodder quality and replaces varieties grown for more than 60 years, bringing hope to millions of poor farmers

ICGV 91114 thriving on poor, rocky soils of Anantapur district

Anantapur is a drought-prone district in the rain shadow area of Andhra Pradesh, India. Although it is subject to frequent droughts and crop failures, over 70% of the cultivated area in the district (0.8–1.0 million hectares) is sown to groundnut each year. Smallholdings of less than 3 hectares occupy 60% of the district, which is the largest groundnut growing area in the world.

Soils in the district are predominantly light textured, gravelly, shallow alfisols with depths varying between 30 and 60 cm. They hold 40 to 70 mm of plant-available water in the soil profile and are low in nutrients. Annual rainfall is low (522 mm compared to the state average of 926 mm) with prolonged dry spells of 45–50 days. The area has an annual average of only 36 rainy days during the rainy season, which are highly variable and erratic in distribution.

In the 1960s, cereal crops such as sorghum and finger millet dominated agriculture in Anantapur District (occupying 50% of the area), and groundnut was a relatively minor crop (grown on 20% of the area). Low rainfall, prolonged dry spells and frequent crop failures reversed this cropping pattern. Today, over 70% of the cultivated area is sown to groundnut because of its ability to survive long dry spells and for its cash value. Further, it is a valuable source of fodder for livestock during dry years or crop failures.

Although the state has released many improved groundnut varieties over the last 20 years, old varieties such as TMV 2 (grown on 80% of the area, released in 1940), JL 24 (15–20% of the area, released in 1978) and Pollachi Red (a landrace) have continued to dominate. New varieties fell short of farmers' expectations. Their seeds were not available, processors were reluctant to adapt their machinery to new varieties and consequently there was price discrimination.

The innovation

Groundnut variety ICGV 91114 came as a breath of fresh air. Bred and developed at ICRISAT headquarters in India, it was derived following the bulk pedigree method from a cross of ICGV 86055 x ICGV 86533. The new variety has a number of desirable features including:

- high yields
- early maturity, in 90–95 days in the rainy season
- tolerance to mid-season and end-of-season droughts
- shelling turnover of 75% on average
- oil content of 48% and protein content of 27%
- good digestibility and palatability of haulms (dry fodder).

Farm family in Anantapur district showing pods of ICGV 91114 groundnut variety

ICGV 91114 was approved for release in the state by the Andhra Pradesh State Seed Sub-Committee in 2006 and was notified in The Gazette of India in July 2007. It was subsequently released as *Devi* (alluding to a Hindu goddess) in Orissa. In Anantapur District, where ICGV 91114 is now replacing TMV 2, ICRISAT's collaborator, Accion Fraterna, has named it *Anantha Jyothi* (meaning Eternal Light in Telugu).

The impact

Farmers prefer early-maturing groundnut varieties with high pod and haulm yields, high shelling turnover, good seed size, and resistance to drought and diseases. ICGV 91114 meets all these preferences and is the most popular dual-purpose groundnut cultivated in India today.

An impact assessment study in the district revealed that the adoption of ICGV 91114 had a pod yield advantage of 23%, with 30% reduction in yield variability and 36% higher net income compared to TMV 2. It was estimated that the annual value of benefits in the district would surpass $500 million, assuming 35% adoption, by 2020–2021.

Despite severe drought conditions in the past 4–5 years affecting seed production and adoption, ICGV 91114 occupied 25,000 ha of the 800,000 ha under groundnut in the district in 2010. The possible economic benefits of wider adoption demonstrate the impact of breeding groundnut for drought tolerance.

Early maturing **chickpea**

Early maturing chickpea, with improved fusarium wilt resistance, high yield potential and good seed quality, has greatly increased crop area and productivity in short-season environments by avoiding terminal drought and heat stress

Chickpea is currently grown in more than 50 countries under a wide range of environmental conditions and cropping systems. Chickpea phenology (time to flowering, podding and maturity) is an important component of crop adaptation. Crop maturity in chickpea ranges from 80 to 180 days depending on genotype, soil moisture, time of sowing, latitude

Chickpea is an important pulse crop in semi-arid Africa and Asia

and altitude. In two thirds of chickpea growing areas, however, the growing season is short (90–120 days) because of the risk of extreme drought or high temperatures at the end of the season (the pod filling stage of the crop).

South and Southeast Asia account for about 84% of the global chickpea area. The crop is mainly rainfed, and is grown in the post-rainy season on receding soil moisture. It often experiences terminal drought and heat stress. Early phenology is also important in the autumn-sown rainfed crop in Mediterranean-type environments such as Australia, and in the summer-grown crop in temperate environments such as Canada, which aim to escape end of season frost. Furthermore, early phenology is needed to promote chickpea in rice fallows, and under late-sown conditions in South Asia.

The innovation

Bi-parental and multi-parental crosses have been used to develop early-maturing chickpea varieties. One of the parents is generally a well-adapted cultivar and the other an early-maturing genotype.

Time to flowering (number of days from sowing to appearance of the first flower) can be recorded with high precision and is a good indicator of subsequent phenological traits (time to podding and maturity). The wide variability in time to flowering in chickpea germplasm provides opportunities to develop cultivars with desirable maturity durations. Selection for time to flowering is effective even in early segregating generations as it is controlled by only a few major genes.

Two different types of chickpea – *kabuli* and *desi* – are recognized by markets and consumers, and serve different culinary purposes. ICRISAT's first extra-short duration *kabuli* cultivar, ICCV 2, matures in only 85–90 days and demonstrates fusarium wilt resistance and heat tolerance. It was developed from a multiple cross that involved five parents and was the first cultivar to show that *kabuli* chickpea could be grown in tropical environments. It was released as *Swetha* in India, *Wad Hamid* in Sudan and *Yezin 3* in Myanmar.

Subsequently, several early-maturing, high-yielding cultivars have been developed, including two new *kabuli* types and four *desi* types. Breeding lines have been developed that mature earlier than either of the parents by combining earliness genes from the two parents. For example, the super-early cultivar ICCV 96029, which flowers in about 24 days at Patancheru, India, was developed from a cross between two early lines, which both flower in 30 to 32 days.

Super-early lines have potential to further expand the cultivation of chickpea in areas and cropping systems where the cropping window is narrow, as well as in specific situations where early podding is highly desirable, such as crops where green immature grains are used as vegetable.

Early-maturing chickpea varieties are adaptable to climate change as they escape terminal drought and heat stresses

Adoption of early-maturing chickpea cultivars has led to an increase in area and productivity in short-season environments

The impact

Adoption of early-maturing chickpea cultivars has led to an increase in area and productivity in short-season environments such as Myanmar and Andhra Pradesh, India. Four early-maturing chickpea cultivars (two each of the *kabuli* and *desi* types), selected from breeding material supplied by ICRISAT, were released in Myanmar in 2000–2004 and rapidly adopted by farmers.

By 2005, these cultivars covered 82% of the total chickpea area in Myanmar. *Yezin 3* (ICCV 2) was the most popular cultivar (occupying 55% of the area), followed by *Yezin 4* (ICCV 88202, covering 22% of the area). The adoption of improved cultivars and crop production practices has led to a remarkable increase in yields and production. Over the past decade (2000–2009), there has been a 2.2-fold increase in both area (129,000 to 282,000 ha) and productivity (651 to 1411 kg ha^{-1}), and a 4.7-fold increase in production (84,000 to 398,000 tons).

The adoption of early-maturing chickpea cultivars has also brought a chickpea revolution in Andhra Pradesh State in India. Chickpea production has increased 9-fold

JG 11 and a new super early chickpea line

(95,000 to 884,000 tons) over the past 10 years (2000–2009). This is a result of a 5-fold increase in area (102,000 to 602,000 ha) combined with a 2.4-fold increase in yield levels (583 to 1,407 kg ha^{-1}).

Over 80% of the chickpea area in Andhra Pradesh is now cultivated with the short-duration improved cultivars JG 11 and KAK 2, which were developed through a partnership between ICRISAT and the Indian national agricultural research system. Andhra Pradesh was once considered to be a low yielding state for chickpea because of its warm, short-season environment, but it now has the highest yield levels in India.

Cultivation of chickpea has been transformed from a subsistence to a market-oriented activity in Andhra Pradesh, providing an excellent example of inclusive market-oriented development.

Cultivation of chickpea has been transformed from a subsistence to a market-oriented activity

Principal Scientist KB Saxena worked with partner scientists to develop the world's first pigeonpea hybrid

Hybrid **pigeonpea**

Cytoplasmic-nuclear male-sterility-based pigeonpea hybrids yield up to 40% more than conventional cultivars

Over the past 50 years, pigeonpea productivity has remained low (750 kg ha^{-1}) despite the release of several new varieties. At the same time, global production (3.5 million tons) has fallen short of ever-rising demand.

To achieve a breakthrough in yield, ICRISAT – working in partnership with the Indian Council for Agricultural Research (ICAR), state agricultural universities, government-owned seed corporations and private seed companies – established an innovative breeding technology to develop commercial pigeonpea hybrids, the first such attempt in any food legume.

Unlike other pulses, pigeonpea is a partially out-crossing species. ICRISAT scientists exploited this feature to make crosses with wild relatives and develop a cytoplasmic-nuclear male-sterility (CMS) system, a prerequisite for hybrid breeding technology.

The innovation

The world's first pigeonpea hybrid, ICPH 8, based on the genetic-male sterility (GMS) system, was jointly released in 1991 by ICRISAT and ICAR. This was a milestone in the history of food legume breeding. Subsequently, five further GMS-based hybrids were released by various state agricultural universities and ICAR institutions.

Although they showed high yields, these GMS-based hybrids did not reach farmers' fields because of the high costs of seed production. The constraints inherent in the seed multiplication of their female parents were a major bottleneck in large-scale hybrid seed production.

The GMS experience led scientists to develop hybrids based on the cytoplasmic-nuclear male-sterility (CMS) system – the most widely accepted system for producing commercial hybrids in a number of field crops. The first breakthrough in this technology was achieved when a CMS system was developed by crossing *Cajanus cajanifolius* (a wild species) and a cultivated pigeonpea line. This CMS system is stable across diverse environments and has excellent fertility restorers.

The CMS system has three lines: the male-sterile A line, the maintainer B line, and the restorer R line. The A line contains the cytoplasm of the wild relative and the nuclear genome of the cultivated pigeonpea, and is male sterile. The B line has both the cytoplasm and nuclear genome of the cultivated pigeonpea, and is male fertile. Crosses between the A and B lines provide seed of the A line. Crosses between the A and R lines lead to the production of hybrid seed.

Once a stable CMS system had been developed, several experimental hybrids were produced and evaluated at ICRISAT and ICAR centers. The hybrids were generally characterized by increased plant vigor, better drought tolerance, disease resistance and better adaptability to varied agro-ecologies. The CMS-based experimental hybrids showed 50–150% standard heterosis (superiority over the popular varieties) for yield.

In multi-location trials, several hybrids demonstrated significantly higher yields than the local varieties. For example, in trials conducted between 2005 and 2008, the medium-duration hybrid ICPH 2671 showed 36% higher yields (2.7 t ha^{-1}) than the local variety *Maruti*.

A second medium-duration hybrid, ICPH 2740, demonstrated 38% higher yields (2.8 t ha^{-1}) than the local variety *Asha*. A short-duration hybrid, ICPH 2433, has also shown promise, yielding 32% more (2.2 t ha^{-1}) than the local variety UPAS 120. In more than 2,000 on-farm trials conducted in five states of India, these hybrids produced an average 30% yield advantage over the best available local variety.

The impact

Climate change will adversely affect productivity of crops as well as livestock, undermining the long-term sustainability of already fragile dryland environments. Under these conditions, pigeonpea hybrids may prove highly advantageous because they grow fast, have greater root and shoot biomass and higher resilience to drought, salinity and diseases than control varieties.

In a joint initiative between ICRISAT and the private sector, the Hybrid Parents Research Consortia (HPRC) were established to increase smallholder farmers' access to hybrid seed. In 2007, Pravardhan Seeds (P) Ltd, a member of the HPRC, selected ICPH 2671 for commercialization and named it *Pushkal* (meaning bountiful in Sanskrit). In December 2010, ICPH 2671 was officially released by the state of Madhya Pradesh.

A second hybrid, ICPH 2740, is poised for release by the states of Andhra Pradesh and Maharashtra. These hybrids consistently showed more than 30% yield advantage over standard cultivars in farmers' fields in single and intercropped systems.

The hybrid seed production technology has been finalized and a target set for expanding CMS-based hybrid pigeonpea cultivation to over 100,000 ha by 2014. As part of this initiative, two hybrids (ICPH 2671 and ICPH 2740) will be promoted in partnership with public and private sector seed organizations, and the National Food Security Mission of the Government of India.

Pigeonpea in eastern and southern Africa

ICRISAT varieties resist wilt, have high yields and large seeds, and are widely grown in Kenya, Malawi, Mozambique, Tanzania and Uganda, increasing farmers' incomes by up to 80%

Until recently, farmers in Africa were unable to fully exploit pigeonpea's potential because local varieties were low-yielding, late-maturing and susceptible to pests and diseases. Small-seeded varieties failed to meet market requirements; market linkages were underdeveloped; and farmers could not access seed of improved varieties because of poor input and technology delivery systems.

These factors effectively deprived farmers in Africa of the benefits of a sizable export market. India alone imports over 254,000 tons of pigeonpea per year, but Africa supplied less than 5% of this demand. Similar high-value niche markets exist in Europe and the Americas. Meanwhile, domestic demand for pigeonpea has grown substantially over the last few years, increasing wholesale prices.

S Silim, ESA Director, with a farmer in a pigeonpea field in eastern Kenya

The innovation

ICRISAT and national program partners have been working together to develop suitable varieties and institutional innovations to help dryland farmers in eastern and southern Africa benefit from pigeonpea. This began with the development of high-yielding, slightly early-maturing, cream-colored, large-seeded and fusarium wilt-resistant varieties for cultivation by smallholder farmers. To address constraints in output marketing and utilization, ICRISAT developed partnerships with private and public sector institutions.

The adoption of improved pigeonpea varieties has catalyzed a process of livelihood transformation for many dryland smallholder farmers in Kenya, Malawi, Mozambique, Tanzania and Uganda. The increasing availability of improved varieties, along with institutional innovations, has enabled farmers to reduce the cost of product marketing, spurring commercialization of the crop.

Recognizing the huge demand for improved seeds, local agro-dealers (called Agrovets) contract farmers to multiply high quality seeds, with the support of the local extension system for training and farmer organization. The commercial produce is marketed through producer marketing groups (PMGs). This collective action enables smallholder farmers to sell quality grain at higher prices.

The impact

ICRISAT has a long and fruitful history of collaboration for breeding with the Ilonga Research Station in Kilosa and the Selian Agricultural Research Institute (SARI) in Arusha, which covers the northern zone of Tanzania. Improved varieties like ICEAPs 00040 and 00053 are becoming very popular. In Babati district – famous for high quality pigeonpea production – adoption of improved pigeonpea varieties has reached 60%, and pigeonpea alone contributes more than 50% of the cash incomes of smallholder farmers.

Arumeru, Babati, Karatu and Kondoa districts in Tanzania are all known for their production of bold cream-colored pigeonpeas. Fifteen years ago, very little pigeonpea was grown in Arumeru District, but as a result of the collaboration between SARI and ICRISAT, pigeonpea is now cultivated throughout the district.

ICRISAT-developed varieties clearly dominate the fields. Only 12 years ago consumption of pigeonpea was not common in Tanzania, but the introduction of palatable varieties ICEAPs 00040 and 00053 has changed all that. Pigeonpea consumption has taken off as the bean crop has largely succumbed to pests and the changing weather patterns that the hardy pigeonpea takes in its stride.

In Kenya, an ICRISAT-led consortium ignited the pigeonpea revolution that brought together partners including TechnoServe, Catholic Relief Services, Kenya Agricultural Research Institute (KARI), and private sector processors and exporters. Successive projects focused on legume commercialization stimulated the growth of local seed production and agro-dealer networks for distribution and marketing. The PMGs facilitated community seed production, local distribution and market access, and helped to increase local producer prices by 20–25% in Nairobi and Mombasa after linking producers to wholesalers.

Pigeonpea consumption has taken off as the bean crop has largely succumbed to pests and the changing weather patterns that the hardy pigeonpea takes in its stride

This has led to tangible gains for poor farmers in these areas where maize has traditionally been the main crop. Unfortunately, the maize crop fails in three out of five years, leaving families to rely on pigeonpea – widely considered a lifesaver and guarantor of livelihoods in these drought-prone areas.

Green pigeonpea is sometimes the only vegetable seen during the dry season in Kenya

The most important change came about through the introduction of medium-duration varieties (ICEAPs 00554 and 00557) that provide two crops a year. The first improved varieties reached farmers of Emali village (Makueni District, Kenya) in about 2003 as a result of field days held at the ICRISAT/KARI research station in Kiboko. This was followed by farmer participatory varietal evaluations and demonstrations. Enterprising women farmers took the lead in demonstrating the pigeonpea technology and proudly call it "our dryland white coffee", as well as "our beef", alluding to its high protein content.

These farmers have also realized the potential of fresh vegetable pigeonpea in the domestic market. Pigeonpea matures when other food reserves are low, making it a popular crop to stave off hunger. Thanks to this high local demand, most of the pigeonpea grown is now sold as green peas at prices almost twice those of the dry grain and yields of green pod average 5 t ha^{-1}.

The commercialization of pigeonpea is enabling farmers to buy valuable assets ranging from mobile phones to productive land and livestock, and is opening viable pathways to move out of poverty. Farmers have invested in small ruminants, milking cows and bullocks, helping them diversify and expand their income sources, reduce vulnerability and mechanize production. It has increased school enrolment of children, as families can now afford to send their children to school. The increased income also allows families to improve food security and increase expenditure on other basic needs.

An ICRISAT-led global team cracks the genome sequence of pigeonpea, an important legume crop

Pigeonpea **genome**

Pigeonpea is the first 'orphan crop', the first 'non-industrial crop' and the second food legume with a completed genome sequence

Pigeonpea is an important crop in Asia, Africa, and Central and South America, grown on nearly 5 million hectares worldwide. It is the world's sixth most important food legume crop. Despite its importance for food security in the world's poorest regions, it has been under-researched in the past. Biotic and abiotic stresses have widened the large gap between its potential yield (more than 3.5 t ha^{-1}) and those obtained in farmers' fields (750 kg ha^{-1}). Rapid advances in genetic improvement have been constrained by a lack of genomic resources, such as molecular markers, mapping populations and genetic maps, coupled with low genetic diversity in the primary gene pool.

Principal Scientist R Varshney leads a global research team to crack the pigeonpea genome sequence

Pigeonpea was neglected until 2005, when intensive efforts by ICRISAT, the CGIAR Generation Challenge Programme, the US National Science Foundation, the Indian Council for Agricultural Research (ICAR) and several other programs led to the development of significant genomic resources in pigeonpea. More recently, a global team comprising several organizations from the USA, Europe and China, and led by ICRISAT, have sequenced the pigeonpea genome.

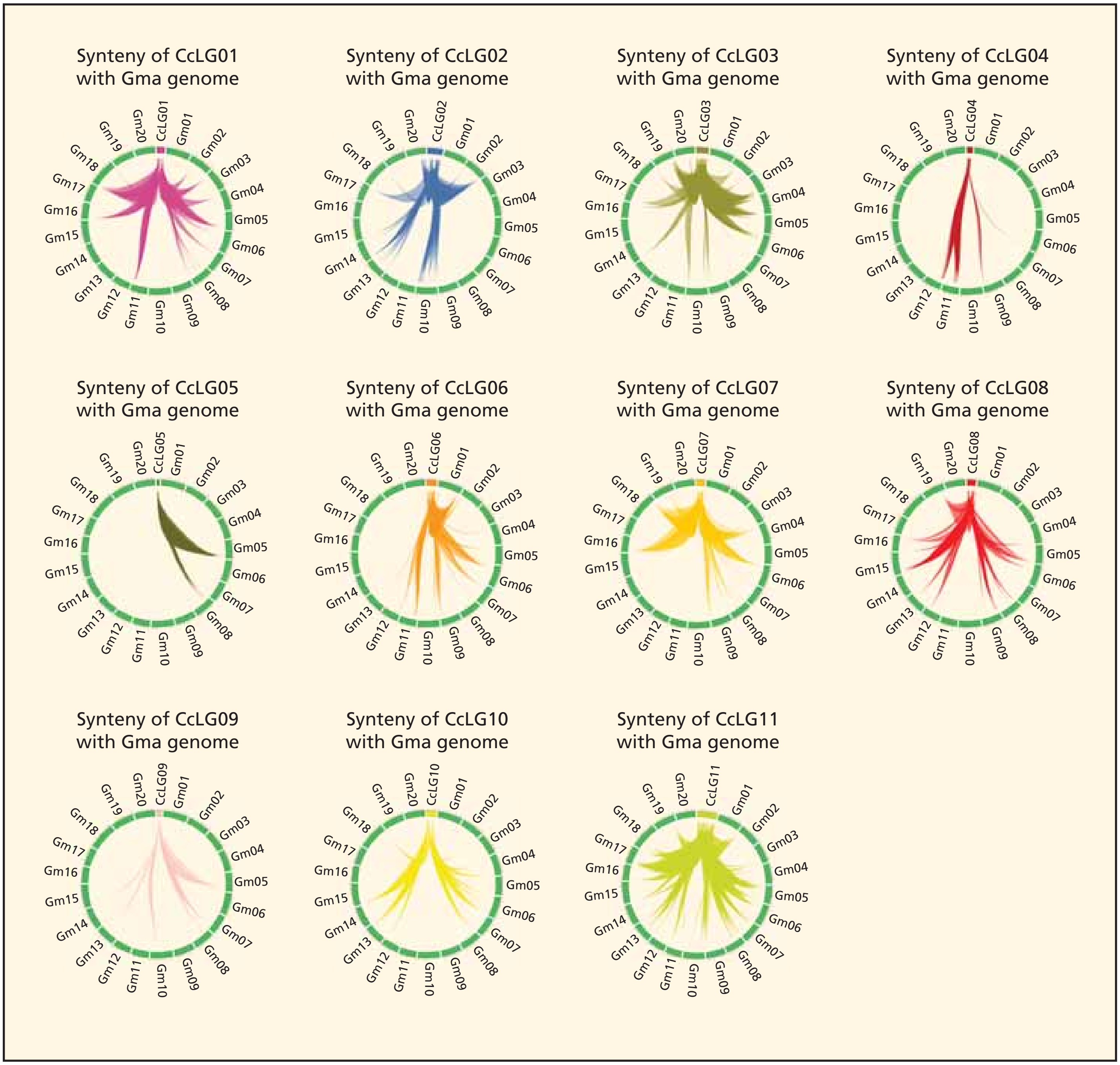
The innovation

To accelerate the use of genomics to improve yield and quality, Illumina – a next generation sequencing technology – was used to generate the draft genome assembly of pigeonpea genotype ICPL 87119 (popularly known as *Asha*). This technology was used to generate a 237.2 Giga base pair sequence, which along with Sanger-based Bacterial Artificial Chromosome-end sequences and a genetic map, was assembled into scaffolds representing about 73% (605.78 Mega base pair) of the pigeonpea genome.

The pigeonpea genome sequence was published in Nature Biotechnology. It is expected that the research will increase the efficiency of pigeonpea improvement by providing molecular breeding tools and approaches to assist conventional breeding.

Genome analysis led to the identification of 48,680 pigeonpea genes. A few hundred of these are unique to the crop and relate to drought tolerance, an important trait that can be transferred to other legume crops such as soybean, chickpea and common bean. Furthermore, comparative analyses revealed that the number of genes predicted in the pigeonpea genome is higher than in other sequenced plant genomes, such as those of cucumber, cacao, grapevine and *Lotus japonicus*. It is, however, comparable to soybean, as shown in Figure 1.

Figure 1. Genome relationships of pigeonpea chromosomes with soybean genome



Source: Varshney et al. (2012) Draft genome sequence of pigeonpea (*Cajanus cajan*), an orphan legume crop of resource-poor farmers. *Nature Biotechnology* 30(1):83–89.

Completion of the pigeonpea genome has made a significant contribution to the genomic resources available for pigeonpea

In Figure 1, soybean pseudomolecules (equivalent to chromosomes) are labeled as Gm and are represented as green boxes. The numbers along each chromosome box denote the sequence length in megabases. Pigeonpea pseudomolecules, labeled as CcLG, are shown with each chromosome as a different color. Syntenic blocks were identified through reciprocal best matches between gene models and block identification using i-Adhore. Each line radiating from a pigeonpea pseudomolecule represents a gene match found in a block between soybean and pigeonpea. Each sub-box within this figure shows the syntenic relationships between a single pigeonpea chromosome and the entire soybean genome.

In order to enhance pigeonpea's molecular marker repertoire, the genome sequence was explored to permit the identification and development of molecular markers. The research identified 309,052 simple sequence repeats (SSRs) and 23,410 SSR primers were designed. Similarly, after aligning the transcript sequences from 12 genotypes, a total of 28,104 novel single nucleotide polymorphisms (SNPs) were identified. In brief, completion of the pigeonpea genome has made a significant contribution to the genomic resources available for pigeonpea.

The impact

The availability of a genome sequence opens up new avenues for pigeonpea improvement. The identification of large-scale SSRs and SNPs spanning the entire genome can help overcome the limitations of insufficient polymorphic markers for genetic mapping and trait identification.

The genome sequence will help harness pigeonpea's genetic diversity by identifying molecular markers and genes for targeted traits, and will allow researchers to develop superior varieties and parental lines of hybrids. It will also be useful in identifying germplasm lines or advanced breeding lines with a broader genetic base for future breeding programs.

Modern genetics and breeding approaches like genotyping by sequencing, marker-assisted recurrent selection and genomic selection will improve the efficiency of pigeonpea breeding. ICRISAT and several national agricultural research systems institutes are developing a road map, in consultation with the Indian Department of Agriculture and Cooperation, ICAR, the Indian Ministry of Agriculture, and the United States Agency for International Development, to use genome sequence information for pigeonpea improvement. This will not only enhance crop productivity, but also help develop short-duration lines with photoperiod insensitivity and thermo-insensitivity genes, so that pigeonpea can be expanded to new niches and fit well into new production systems.

Farmers in Mali select panicles of preferred varieties from their own fields

Guinea-race **sorghum** hybrids

Sharing the benefits of hybrid vigor with West African farmers, while retaining the adaptation and quality traits of local germplasm

Sorghum varieties belonging to the Guinea-race combine high grain quality with excellent adaptation for major parts of the Sudanian zone of West and Central Africa. Despite their exceptional yield stability, however, yield levels rarely exceed 2 t ha^{-1} in farmers' fields.

In 1999, researchers from ICRISAT, the Malian Institut d'Economie Rurale (IER), and the Institut National de l'Environment et des Recherches Agricoles (INERA) in Burkina Faso began to grapple with ways of unlocking the genetic potential of these sorghums, to enhance the productivity of this staple crop of West and Central Africa.

The innovation

One of the approaches adopted by researchers was the development of hybrids based on well-adapted Guinea-race parents. The benefits of hybrid vigor have long been reaped in India, where ICRISAT has played a pivotal role in developing parental lines and sorghum hybrids have been widely adopted. ICRISAT has shown experimentally the potential benefit of hybrid vigor under both favorable and drought-prone conditions in eastern and southern Africa. However, this progress was made with other sorghum races that lack the specific adaptive characteristics required for successful production in the Guinea-race growing belt that stretches from Senegal across to Nigeria and Cameroon in West and Central Africa.

The ICRISAT–IER–INERA team thus set out to create the first hybrid parents based on Guinea-race germplasm with adaptation to West African conditions. A major task was to develop the first Guinea-race female parents based on the cytoplasmic nuclear male-sterility (CMS) system. The genetic materials used for this task included local varieties from Mali, inter-racial (Guinea-Caudatum) breeding lines from the IER program, and Guinea-race accessions of worldwide origin from the World Sorghum Collection in the ICRISAT genebank in India.

Within five years the first female parents were obtained using methods similar to those employed for hybrid pigeonpea, although the crossing work could begin immediately with previously available CMS lines such as CK60A. The first experimental hybrids were produced in 2004 on new female parents of both inter-racial and Guinea-race backgrounds. Regional testing of new sorghum hybrids was conducted in collaboration with the national research programs in Mali (IER), Nigeria (Institute for Agricultural Research), Burkina Faso (INERA), Senegal (Institut Sénégalais de Recherches Agricoles), and Ghana (Selian Agricultural Research Institute). The first four sorghum hybrids with Guinea-race parentage were released in Mali in 2008.

The impact

Extensive on-farm testing of the new guinea-race hybrids was carried out in Mali from 2009 to 2011. This enabled hybrid yields to be thoroughly compared with a well-adapted control variety, *Tieble*, under farmer-managed conditions. The average yield of all eight hybrids showed 28% superiority over *Tieble*. Two of the released hybrids, *Fadda* and *Sewa*, produced 450 kg ha^{-1} more on average than *Tieble*, which amounted to 46% yield superiority across all environments.

Furthermore, these hybrid yield superiorities were expressed across the entire range of productivity conditions. In the nine least productive trials (with mean yields of less than 1.5 t ha^{-1}), *Fadda* and *Sewa* still produced 450 kg ha^{-1} more than *Tieble*. Likewise, the hybrids showed yield advantages across the full range of soil fertility conditions and sowing dates.

These yield advantages are truly exciting as they meet farmers' demands for increased productivity, while maintaining grain quality and retaining (or even enhancing) yield stability. And this is just the beginning. The Guinea-race is the most diverse of sorghum races and ICRISAT has just begun to explore the structure of this diversity and the patterns of heterosis (hybrid superiority over the parents).

Initial results show that high heterosis can be obtained when parents from humid West Africa, East Africa, southern Africa and even Asia are crossed onto a West African tester. The accessions that give the highest heterosis in crosses with a West African tester came from Cameroon, China and Zimbabwe.

Farmer seed producer organizations are now being empowered to produce hybrid seed through 'learning by doing', with training and technical support from IER and ICRISAT. Farmers are excited about hybrid seed production, as it enables them to combine the dual goals of increasing income through the sale of hybrid seed, and that of food security with grain produced by the male parent. Emerging seed companies have bought and marketed all the hybrid seed that has been available every year since 2009 when large scale production began. Malian farmers and researchers are enthusiastically pursuing sorghum hybrids as a way of meeting farmers' and consumers' needs. Meanwhile sorghum is changing from a subsistence crop to an increasingly important source of income for farmers.

Extra-early **pearl millet** hybrid

Inter-institutional collaboration integrates conventional, participatory and marker-assisted breeding methods to develop extra-early pearl millet hybrid HHB 67 Improved, which has enhanced downy mildew resistance and yield

Pearl millet hybrids have shown a 25 to 30% grain yield advantage over open-pollinated varieties, leading the national agricultural research system and a large number of private seed companies in India to develop an interest in breeding and marketing hybrid cultivars. As a result, hybrid development has been the major thrust of pearl millet breeding programs in India over the past 25 years, supported by hybrid parents breeding research at ICRISAT.

In 1990, CCS Haryana Agricultural University (CCSHAU) released the hybrid pearl millet HHB 67, the earliest maturing pearl millet hybrid (62–65 days from sowing to harvest) anywhere to date. This was rapidly adopted by farmers in northwestern India and was grown on approximately 774,000 ha in the most drought-prone areas of southern Haryana and central Rajasthan at the peak of its adoption in 2002.

Few alternative hybrid cultivars were available for this zone and single-cross hybrids are known to be vulnerable to downy mildew (DM) epidemics, with production losses nationally of up to 30% when an epidemic occurs. ICRISAT therefore initiated a proactive maintenance breeding effort in 1991 to develop versions of HHB 67 that were more resistant to DM. HHB 67 Improved was the higher-yielding and more disease resistant result.

The innovation

The hybrid HHB 67 and its more DM resistant replacement HHB 67 Improved, were developed as a result of coordinated inter-institutional research. Scientists at CCSHAU produced an inbred restorer line (H 77/833-2) from a local landrace from Siwani District in India. This was crossed onto cytoplasmic male-sterile line 843A to produce HHB 67. The hybrid seed parent (843A) and its maintainer line (843B) were developed at ICRISAT-Patancheru by selection for residual variability for DM resistance in an A/B-pair that had been bred in the USA at the Fort Hays Experimental Station of Kansas State University.

The DM resistance of HHB 67 was expected to be overcome by the pathogen sooner rather than later, as has always been the case with popular pearl millet hybrids grown in India. Fortunately, farmers were able to continue large-scale cultivation of HHB 67 until 2007. By this stage, however, strains of the DM pathogen capable of overcoming its resistance had become prevalent in much of Haryana.

Mapping of DM resistance indicated that the resistance originally present in this hybrid had come – at least in part – from the restorer line. In 1991 (a year after the release of HHB 67), a conventional backcross program was initiated at ICRISAT-Patancheru with the aim of maintaining the positive attributes of 843A/B (earliness, large grain size, good tillering, excellent combining ability and dwarf height), while improving its DM resistance. Using one to two cropping seasons per year, a dozen more DM-resistant versions of 843A/843B were developed by December 1999.

Further developments came from another inter-institutional effort involving ICRISAT and advanced research institutes in the UK, supported by the Plant Science Research Programme of the UK's Department for International Development. Two genomic regions containing quantitative trait loci (QTL) for DM resistance were identified in the inbred restorer line (H 77/833-2), and two different DM resistance QTL were added to it from a DM-resistant selection in another elite restorer line (ICMP 451-P6).

Marker-assisted backcrossing was used to pyramid DM resistance alleles from the two QTLs from ICMP 451-P6 into the genetic background of H 77/833-2. Initiated in 1997 at ICRISAT-Patancheru, this process was completed in early 2000, resulting in the development of 11 product lines, similar in appearance to H 77/833-2, and including DM resistant restorer line H 77/833-2-202.

The marker-assisted backcrossing used to breed these restorer lines not only accelerated the process, it also enabled precision breeding, using knowledge of the genomic regions being transferred from the resistance donor. Testcross trials conducted in the rainy season of 2000 at ICRISAT-Patancheru, and across six environments in India in the rainy season of 2001, identified two new hybrid combinations for further assessment. These were submitted simultaneously to state trials in Haryana and national trials of the All-India Coordinated Pearl Millet Improvement Program by the team at CCSHAU.

In 30 trials conducted over three years, HHB 67 Improved yielded on average 1,992 kg ha^{-1} of grain (10.5% more than HHB 67), 4.5 t ha^{-1} of stover (9.8% more than HHB 67), and reached flowering in 42 days (2 days more than HHB 67). In a greenhouse seedling screen for DM reaction under high disease pressure, HHB 67 Improved was free of DM compared to disease incidence of 97.8% on HHB 67. Based on its superior performance for DM resistance and yield, HHB 67 Improved was released in 2005 by state and national authorities in India, and seed started to reach farmers' fields in Rajasthan and Haryana the next year. HHB 67 Improved was the first marker-assisted field crop bred in the public domain to reach farmers' fields in India.

The impact

Hybrid seed production of HHB 67 attained a peak of 2,835 tons of certified seed in 1999, nine years after its release. Seed production of HHB 67 Improved reached 3,491 tons in 2011, only six years after its release. At the peak of its adoption in 2002, HHB 67 was grown on about 774,000 ha. By 2011, HHB 67 Improved had spread to 875,000 ha, with Rajasthan accounting for 768,000 ha (16% of the state's total pearl millet area) and Haryana accounting for 107,000 ha (21% of the state's pearl millet area).

The net additional benefits to the farming community from cultivation of HHB 67 Improved, compared to the local landrace varieties in Rajasthan and HHB 67 in Haryana, reached $13.5 million in 2011 alone. On average, producers of HHB 67 Improved seed earned a net income of $1,460 ha^{-1}, with a total net benefit of $6.4 million in 2011. Hybrid seed multiplication also generated 186 person days ha^{-1} of employment (ten times more than grain and stover production), resulting in a total of 900,000 person days of employment. Of this, 45% comprised women laborers.

HHB 67 Improved has helped stabilize pearl millet production for farmers who grow short-duration hybrids under dryland conditions. Its higher yield performance has released land for crop diversification, including cultivation of cash crops such as sesame, cluster bean and food legumes.

Furthermore, the short duration varieties of both of these popular hybrids have facilitated the cultivation of winter season rotational crops such as mustard, wheat and chickpea, thus doubling cropping intensity and substantially increasing farm household incomes compared to those obtained previously by growing pearl millet landraces.

The marker-assisted backcrossing used to breed these restorer lines not only accelerated the process, it also enabled precision breeding

Before the advent of HHB 67 Improved, pearl millet farmers battled with downy mildew disease (in left hand)

Sweet **sorghum**

A smart, multipurpose (food, feed, fodder, fiber and fuel) crop adapted to drought and climate change provides higher incomes for farmers

In the wake of steeply rising fossil fuel prices, interest in biofuels has grown worldwide. In addition to the leading biofuel feedstocks such as sugarcane, sugarbeet, cassava, rapeseed and maize grain, alternatives are emerging to help meet mandated blending requirements. Alternatives are also needed in the tropics and sub-tropics because some crops, such as sugarcane, require about a year to grow and need large quantities of water and fertilizers; sugarbeet demands a cooler climate, and is water and nutrient thirsty; and maize requires significant quantities of water and nutrients.

In recent years, sweet sorghum has gained popularity as an alternative feedstock for biofuel production. Juice extracted from its stalks can be used to produce bioethanol, jaggery and syrup, and the bagasse (leftover stalks after juice extraction) can be used to cogenerate power, as animal fodder and as organic fertilizer after composting. It possesses sugar-rich stalks, and uses water and nutrients efficiently. It also produces grain for food. With sweet sorghum, the food–fuel–feed trade-offs are negligible.

Principal Scientist B Reddy worked with partner scientists in the genetic enhancement of sweet sorghum

The innovation

Research in genetic enhancement at ICRISAT has shown that there is good variability for stalk sugar content and juice volume in sweet sorghum, providing ample scope to improve genotypes for high sugar/ethanol yield. Significant genotype-by-environment interactions meant that cultivars need to be customized for different agro-ecological zones and seasons. A mix of varieties and hybrids with differing maturities that adapt well to rainy and post-rainy seasons, and have resistance to shootfly, can extend the feedstock supply to the industry.

There is heterosis for total stalk sugars, indicating that hybrids produce more sugars than varieties. Being a high biomass crop, sweet sorghum lends itself to first generation (stalk sugars conversion through fermentation), as well as second generation (cellulose conversion) technology-based ethanol production.

Work with partners in India on the sweet sorghum-based ethanol production value chain has shown that adopting the right cultivars and crop production technology, coupled with input and technical backstopping, enhances on-farm yields. Moreover, when grain and stalks are included, cultivating sweet sorghum is more economically valuable than grain sorghum or maize.

Between 40 and 50 liters of ethanol can be produced per ton of sweet sorghum stalk with efficient crushing technology. Sweet sorghum bagasse with residual leaves is a valuable feed resource that commands a similar price as grain sorghum stover. Complete feed blocks based on bagasse are highly palatable, cost effective, and improve yields of both milk (cows) and meat (sheep). Syrup from sweet sorghum juice can also be used as a feedstock even after nine months in storage (enabling a distillery to run for longer).

In India, the sweet sorghum value chain for biofuel production and use as a blend with gasoline yields a net energy balance of 7.5 and reduces greenhouse gas emissions by 86% compared to fossil fuels. The sweet sorghum value chain for ethanol will be sustainable, provided the distillery is a multi-feedstock unit, the supply chain is professionally managed, production and marketing of by-products (bagasse) can be organized, and the government puts in place a policy framework with incentives and favorable pricing of ethanol compared to petrol.

When grain and stalks are included, cultivating sweet sorghum is more economically valuable than grain sorghum or maize

ICRISAT scientists explain the benefits of sweet sorghum to a Philippine envoy during their visit to ICRISAT field trials

An assembly of village people at the inauguration of the first crushing and syrup unit at Ibrahimbad village near the ICRISAT campus in Patancheru

The impact

ICRISAT and its partners in the Philippines have been instrumental in creating awareness of the potential value of sweet sorghum, its cultivation, research needs and use as a feedstock for bio-ethanol production. Many farmers in Cabiao, Candaba and Ilocos Norte are cultivating ICRISAT-bred sweet sorghum variety SPV 422 (which farmers refer to as Sweet Philippine Variety) and are reaping benefits by selling stalks and grain.

On average, farmers harvest 40–55 t ha^{-1} stalks and 4–5 t ha^{-1} grain. The ratoon crop (which results from the rejuvenation of the stubble of a previous crop) offers 40–50% higher yields than the seed crop. Two varieties (SPV 422 and ICSV 93046) are being released in the Philippines for commercial cultivation and Bapamin Enterprises, a farmer cooperative, is marketing 1,000 liters per month of vinegar made from sweet sorghum. In China, sweet sorghum is also being used as biofuel feedstock. ICRISAT-bred sweet sorghum cultivars are increasingly being cultivated as a forage crop in Cambodia, Ethiopia, India, Jordan, Mali, Mozambique, Nigeria, Syria and Uzbekistan.

Sweet sorghum, the smart crop, provides income for farmers from the sale of grain and stalks, either to distilleries or to fodder markets, truly demonstrating the inclusive market-oriented development approach.


Director General WD Dar, Former CGIAR Chair Kathy Sierra, CLL Gowda, and HD Upadhyaya in the medium-term cold room. ICRISAT conserves more than 120,000 accessions of its crops from 144 countries in its genebank

Genetic resources for **food security**

ICRISAT's genebank conserves more than 120,000 accessions and supports the global crop improvement community to develop improved cultivars

The RS Paroda Genebank at ICRISAT's headquarters in Patancheru, India, is one of the world's largest repositories of genetic resources of its mandate crops, and at present conserves more than 120,000 accessions from 144 countries. From this facility, ICRISAT engages in the assembly, conservation, maintenance, characterization, evaluation, documentation and distribution of germplasm of its mandate crops – sorghum, pearl millet, chickpea, pigeonpea and groundnut and their wild relatives; and six small millets – finger millet, foxtail millet, barnyard millet, kodo millet, little millet and proso millet.

These accessions have been assembled through donations from various institutions and by launching germplasm collection missions in areas of origin and diversity jointly with national agricultural research systems (NARS), universities and international institutions. The plant genetic resources held by the genebank contribute enormously to achieving the Millennium Development Goals of food security, poverty alleviation, environmental protection and sustainable development.

All incoming germplasm samples received in India are examined by the Indian Plant Quarantine Services with the assistance of the National Bureau of Plant Genetic Resources, India, to exclude or eradicate exotic pests and diseases.

ICRISAT has also established three regional genebanks in Niamey, Niger; Nairobi, Kenya; and Bulawayo, Zimbabwe. These conserve working collections and mini core collections of mandate crops to cater to the research needs of national programs, and also provide safety duplication of specific subsets of materials, including national collections from these regions.

The genebank

Assembly is the initial step in *ex-situ* conservation of germplasm resources. Since collection and conservation are expensive, this is undertaken only after a critical assessment of the need to do so. Only unique landrace germplasm accessions that are not represented in the collection are assembled/collected.

The genebanks follow international standards of conservation. Germplasm accessions are maintained by monitoring for seed viability and quantity at regular intervals. Accessions showing critical seed viability (<85% germination) and seed quantity in the medium-term store (<50 g for cereals and <100 g for legumes) are regenerated as the situation warrants (usually once every 5–10 years).

Accessions are characterized and evaluated using a set of internationally accepted descriptors for stable botanical characters, and a few agronomic and seed quality traits. Characterization and evaluation data facilitate the preliminary selection of germplasm by users, while information on country of origin, location of collection and other passport data permit the selection of germplasm based on geographic origin, and the identification of gaps in the collection for further exploration.

Documentation is essential for good genebank management and to allow efficient and effective use of germplasm. The data are maintained in the Genebank Information Management System, which facilitates sharing and easy retrieval of information. The passport and characterization data are made globally accessible as international public goods (IPGs) through the ICRISAT website (www.icrisat.org) and the CGIAR's System-Wide Information Network for Genetic Resources (SINGER). ICRISAT is duplicating collections and has over 86,000 accessions at the Global Seed Vault at Svalbard, Norway.

The innovation

Glass house facility for wild arachis regeneration

Although there was a substantial increase in the number of accessions in the early 1990s, there was no corresponding increase in their use by scientists, indicating that the full potential of the collections was not being realized. The main deterrents were the large size of the collections, coupled with breeders' differing requirements for traits of interest, which required exhaustive, costly and time-intensive multi-location evaluations.

The core collections (10% of entire collection) and mini core collections (10% of the core, or 1% of the entire collection) represent the genetic diversity of the cultivated species of ICRISAT's mandate crops. These collections were developed as a gateway to enhanced use of the germplasm. These subsets have now been extensively used by researchers to identify trait-specific germplasm for breeding programs at ICRISAT, and by partners in NARS and advanced research institutes (ARIs) globally. Scientists in many other countries are now developing mini core collections in various crop species following approaches suggested by ICRISAT scientists. These mini core collections are IPGs and are the subject of further investigation in research programs underway in Canada, China, Germany, India, Kenya and the USA.

Evaluation of 171 sets of mini core collections by ICRISAT, NARS and ARI scientists in 24 countries in Asia, Africa, Europe, Oceania and the Americas has resulted in the identification of new sources of tolerance to drought, salinity, heat and water logging, as well as disease resistance. Sources have also been identified for improved agronomic traits (early-maturity, high yield, seed size) and quality (oil, protein, iron, zinc, calcium) in ICRISAT's mandate crops.

Molecular characterization of mini core and trait-specific subsets is unraveling further information on the usefulness of these germplasm accessions for allele mining and developing high-yielding cultivars with a broad genetic base.

Wild relatives are good sources of resistance to biotic and abiotic stresses and have been used to improve resistance, but they are agronomically poor. ICRISAT used wild relatives in chickpea and groundnut to improve maturity duration, seed size and yield, and for accessing novel alleles.

The passport and characterization data are made globally accessible as international public goods (IPGs) through the ICRISAT website

The impact

One of ICRISAT's strategic objectives is to serve as the world repository for the germplasm of its mandate crops, including wild relatives. Its genebank has played a key role in restoring germplasm to national research programs in several countries to replace their lost collections. With the erosion of on-farm genetic diversity and relatively reduced exchange of germplasm among countries, the ICRISAT genebank has become a major source of genetic diversity for crop improvement. It has also promoted testing and release of several of its germplasm accessions directly as superior cultivars in many countries.

To date, more than 1.4 million samples of nearly 100,600 germplasm accessions have been shared with collaborators in 145 countries. NARS partners have released more than 800 varieties in 79 countries utilizing germplasm and breeding lines from ICRISAT. Morphological mutants such as dwarfs, and leaf and stem variants identified during characterization have been extensively used in academic studies.

Field view of pearl millet regeneration

The HPRC enables the private sector to access parental lines of varieties and hybrids developed by ICRISAT

Hybrid Parents **Research Consortium**

Public–private partnerships produce scientific innovations and products for the poor

Crop improvement programs at ICRISAT work with partners to develop improved cultivars, including varieties, hybrids and hybrid parents that have potential for increased yields of grain and/or fodder on farmers' fields, leading to enhanced crop productivity and production. These partners include national agricultural research systems (NARS), advanced research institutes (ARIs) in developing and developed countries, public and private sector seed companies and farmers.

ICRISAT's crop improvement research is supported by funds from public and philanthropic donors and, more recently to some extent, from the private sector. Research products that include breeding material, hybrid parents, unfinished varieties and trait-based populations are in the public domain as international public goods (IPGs), and are accessible to public research institutions and private seed companies. Between 1976 and 2011, partners in 79 countries released over 800 cultivars (varieties and hybrids) using germplasm and breeding material from ICRISAT.

The innovation

ICRISAT set up the Hybrid Parents Research Consortium (HPRC) in 2000, as a partnership model for sorghum and pearl millet hybrid parents' research. Pigeonpea was included in the consortium in 2004. This Consortium explicitly recognizes the value of private sector seed companies as partners in hybrid cultivar development, seed production and marketing of hybrid seeds. Private seed companies contribute small grants annually (for a crop consortium under a 5-year timeframe) to support core crop improvement research at ICRISAT. All ICRISAT-bred materials remain in the public domain as IPGs and no seed company has exclusive rights.

The HPRC is currently in its third phase. Mutually agreed guidelines apply to its operations, including an Advisory Committee comprising representatives from the private sector and ICRISAT.

Through the Standard Material Transfer Agreement, scientists in public research institutions have free access to the improved breeding materials developed by the consortia. Breeding materials under development are initially available only to HPRC members in the private sector. Non-members have access to parents of released hybrids (on payment of designated fees) three years after these have been provided to Consortium members. There is no lateral transfer of these materials, and ICRISAT deals with all seed requests.

Private sector seed companies that are members of the Consortium and all public sector institutions are invited to participate in field days at ICRISAT to select the materials of their choice at any stage of their development from early generation segregating materials to near-finished hybrid parental lines. From time to time, these seed companies provide ICRISAT with feedback on the performance of ICRISAT-developed materials and on farmers' needs and preferences.

Representatives of Pioneer Seeds contribute to the Pearl Millet Seed Consortium

The impact

A formal survey of the impacts of ICRISAT's hybrid parents' research on hybrid development in the public and private sector seed companies (based in India) was undertaken in 2012.

ICRISAT-bred materials have a high impact in terms of the number of hybrids developed and their sustainability in the market

In sorghum, five member companies of the consortium are based outside India. Six companies are within India, of which four (67%) directly utilized the parental lines of ICRISAT germplasm. Of the 14 new hybrids commercialized by private sector partners, eight (57%) were developed using ICRISAT-bred materials (A-, B- or R-lines). ICRISAT contributed 100% of the breeding materials used by two seed companies to develop six hybrids; another two companies received a 50% contribution used to develop four hybrids. The longevity of the hybrids developed using ICRISAT-bred genetic materials was 8–20 years in the market, compared with 3–7 years for the hybrids of non-ICRISAT-bred lines, (except for one hybrid which has been cultivated for the last 14 years). ICRISAT-bred materials had a high impact in terms of the number of hybrids developed and their sustainability in the market.

Twenty-one companies producing pearl millet seed were surveyed in India. Seven used 100% ICRISAT-bred parental lines to develop 44 hybrids, while another six companies used between 17 and 86% of ICRISAT parental lines to develop 18 hybrids. A total of 103 hybrids were developed between 2000 and 2010 by the seed companies, of which 62 (60%) used ICRISAT-bred materials (A-, B- or R-lines). The longevity of the hybrids developed from ICRISAT-bred genetic materials ranged from 2–10 years in the market, mostly due to resistance to downy mildew disease. This compared well to the hybrids of non-ICRISAT-bred lines, whose longevity ranged from 2–6 years. One hybrid developed using ICRISAT-bred parental lines has been in the market for 20 years and another for 26 years. Results indicate that the hybrids developed using ICRISAT-bred materials had a high impact in terms of numbers and sustainability.

In pigeonpea, seven seed companies are members of the consortium, of which one is from outside India. Between 2009 and 2011, several ICRISAT-bred materials (A-, B- and R-lines) were supplied to begin the hybrid breeding program, as well as promising hybrids for evaluation and promotion. The evaluation of hybrids by these seed companies provided useful insights, which led to the release of hybrid ICPH 2671 in December 2010 by the State Variety Release Committee in Madhya Pradesh. Two promising hybrids (ICPH 2740 and ICPH 3762) have been promoted for further evaluation in farmers' fields.

Concerted efforts are underway by seed companies to produce pigeonpea hybrids. Since hybrid seed production is dependent on the population of insect pollinators, ICRISAT has provided information on specific ecologies suitable for hybrid seed production to

Principal Scientist KN Rai, with megaphone, addresses a group of private sector seed company officials during a field visit

the seed companies. Pigeonpea hybrids are now on the verge of commercialization and soon farmers will reap the benefits of this technology.

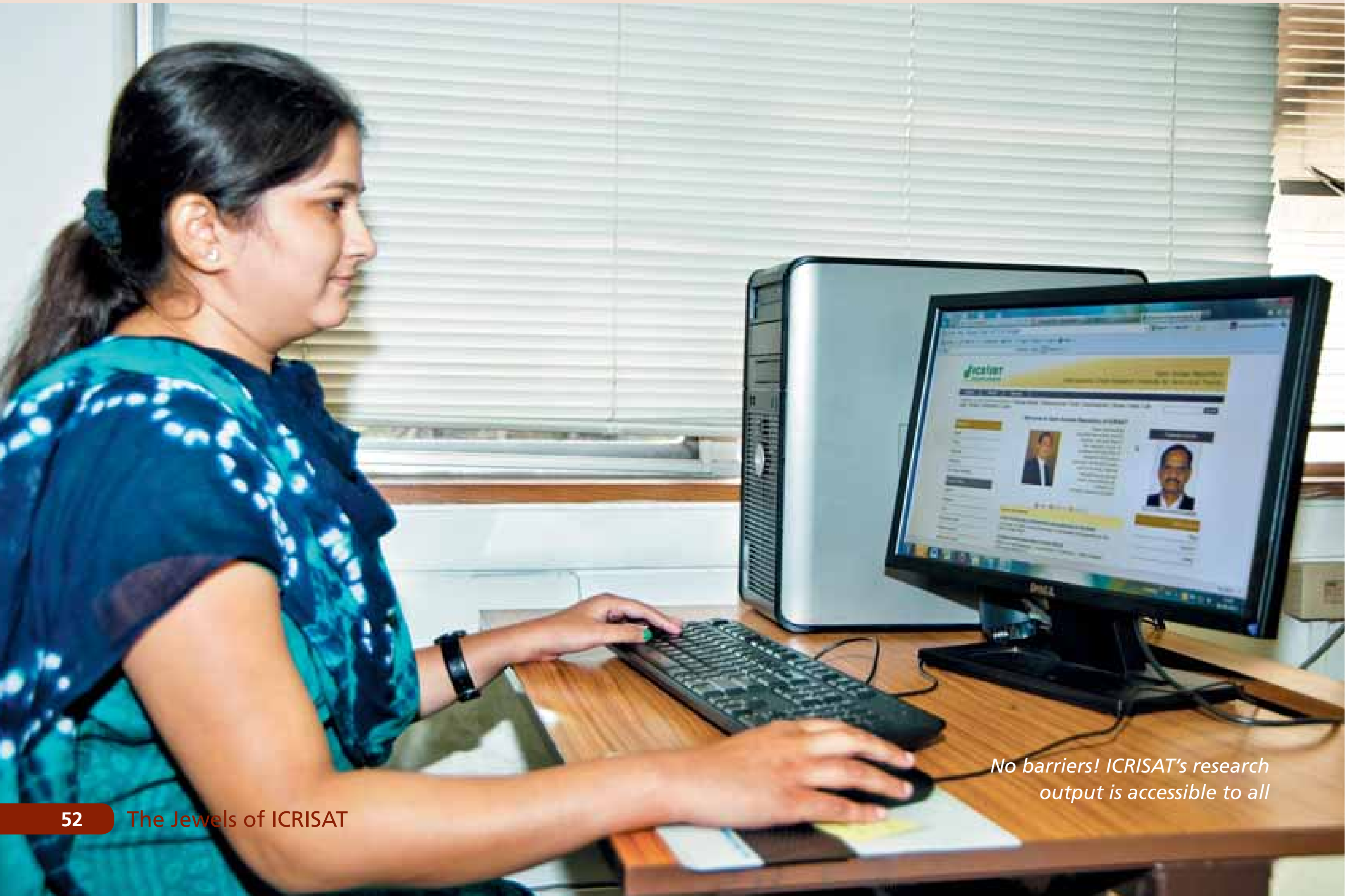
The HPRC has enabled ICRISAT to strengthen linkages with private sector seed companies within and outside India, which in turn have benefited tremendously from the partnership. Farmers too have benefited, through access to seed of improved hybrids at affordable costs, and led to enhanced incomes.

This public–private partnership is the first in the CGIAR to tap private sector funds for public research and optimize synergies between them to swiftly move research products to farmers. It was also the precursor for the Agribusiness Innovation Platform at ICRISAT. Other CGIAR Centers have since used the HPRC model in hybrid parents research.

All ICRISAT-bred materials remain in the public domain as international public goods

Open access repository

An interoperable open access institutional repository for ICRISAT knowledge products



No barriers! ICRISAT's research output is accessible to all

Open access provides free, immediate and permanent online access to the full text of peer-reviewed research documents for anyone, webwide, without any severe restrictions on use. It has had a great influence on science and scholarship. Open access to research information related to agriculture is critical as it has the power to promote greater distribution of knowledge and enhances the potential for innovation.

Roughly 25,000 peer-reviewed periodicals are published around the world. According to CAB Abstracts, agricultural and related research is reported in 7,500 periodicals published in many countries. Other than a few hundred open access journals, many of these 7,500 are commercial. In addition to core journals, agricultural research information is scattered in grey documents such as research reports, think-tank assessments, theses, conference proceedings, monographs and field notes.

Over the last 30 years, escalating journal prices have deterred academic and research libraries in developing and developed countries from subscribing. Traditional, subscription-based journals limit access to research information by treating knowledge that is essentially a public good as a commodity. Yet access to articles published in journals reporting agricultural research is key for agricultural researchers.

The toll-access journal system, set up some 350 years ago, served us well until a few decades ago. Having evolved, for historical reasons, largely to serve the needs of North–North knowledge exchange, it failed to recognize the aspirations of the South. The value of South-to-North knowledge flow was well demonstrated when the avian flu and swine flu epidemics struck, when the speedy exchange of research results and data was critical.

To overcome these problems and promote the idea of open access research outputs, ICRISAT set up an open access repository to make all documented knowledge generated in the past four decades by its scientists accessible to all. This enables the free flow of research information between north and south, east and west, helping research to progress much more effectively.

The innovation

Open access through an interoperable repository system is an innovation – a clever use of web and related technologies to enhance webwide visibility of local research. The institutional repository is a simple platform that facilitates local researchers to archive their research outputs. The repository platform adheres to internationally agreed standards for metadata interoperability, enabling individual institutional repositories easily to form part of a global network.

http://oar.icrisat.org

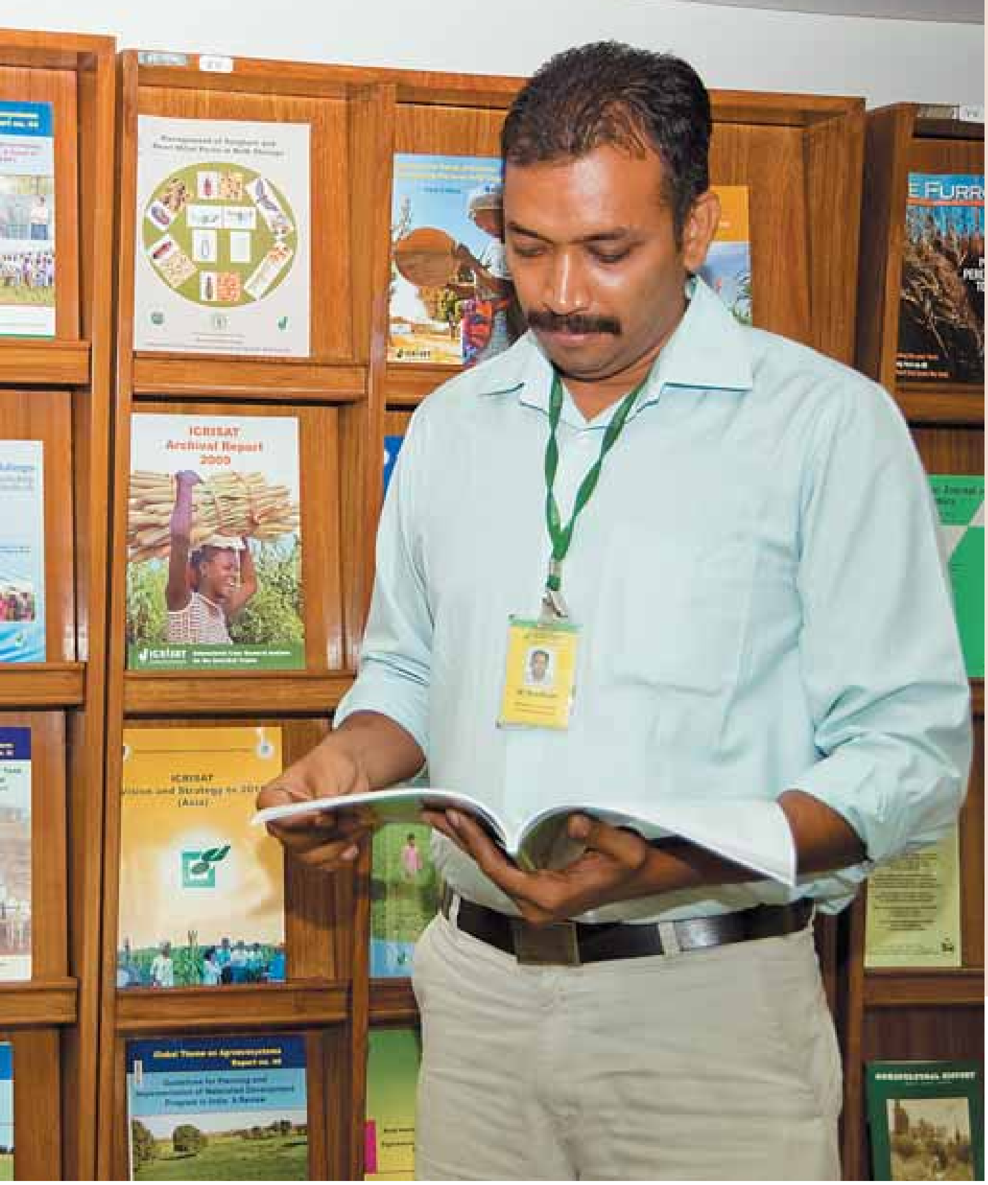
ICRISAT's first interoperable open access institutional repository was set up in early 2009, using an open source software called Dspace. Since May 2009, when an institution-wide open access mandate was endorsed, the repository's holding has increased to 3,000 journal articles and institutional publications.

In order to improve the operation of the repository, in May 2011 ICRISAT's library made available all the documents published in its 40 year history in a new, customized repository (http://oar.icrisat.org) using an open source software called EPrints.

In July 2012 the new repository held over 5,500 documents published since 1973, authored by 1,289 ICRISAT scientists. They include 3,418 journal articles, 826 conference papers, 836 monographs, 234 book chapters and 191 theses. These documents are the result of collaboration between ICRISAT researchers and scientists in more than 90 countries and have all been linked using *Google Scholar*.

Documents can be accessed and located in many different ways. The results can be filtered by names of collaborating institutions and countries and, where available, the funding agency. A digital showcase of ICRISAT's research outputs, the repository is freely accessible to all national agricultural research system partners and other curious minds.

Library and Information Services Manager, M Madhan, does not need to open a book anymore – these and several thousand publications are now available at everyone's desktop through the open access repository



A digital showcase of ICRISAT's research outputs, the repository is freely accessible to all partners and other curious minds

The impact

The repository metadata are harvested by special Open Access Initiative (OAI) service providers such as *OAIster*, *Scientific Commons* and *BASE*, while the contents of the repository are indexed by search engines including *Google* and *Google Scholar*. The bibliographic data of the repository contents are also indexed by AGRIS. In July 2012, around 50% of the repository's users were driven by *Google* and 10% by *Google Scholar*. In all, the repository has counted more than 75,000 downloads as of June 2012.

Every month, the repository serves no fewer than 3,500 unique visitors from many countries. Excluding India, the top 10 countries to use it are the USA, France, Pakistan, Ethiopia, Germany, Iran, United Kingdom, Japan, the Philippines and Kenya. The repository has become a particularly valuable resource for global agricultural researchers who are working on chickpea, pigeonpea, sorghum, millets and groundnut.

Seed systems in sub-Saharan Africa

Facilitating access by poor farmers to seeds of ICRISAT's improved varieties in sub-Saharan Africa

As commercial agriculture grows in importance, seed systems need to deliver high-quality seed of a range of crops and varieties that suit both the consumption needs of the rural population and market demands of agro-processors. With increasing commercialization of African agriculture, the balance between these two needs is expected to shift toward the demands of market-responsive processors and distributors.

Numerous constraints limit the performance of seed systems in sub-Saharan Africa including limited access to seed of new varieties; limited supplies of breeder,

foundation and certified seed of farmer and market-preferred varieties; non-functional national variety release committees; and the lack of enabling policy and institutional environments. This has resulted in *ad-hoc* public sector interventions that frequently impede efforts to develop a sustainable agricultural input supply system.

The innovation

ICRISAT is working with its partners to support the development of open seed markets and local seed companies that can supply quality seed of improved varieties at affordable prices. The entrepreneurial spirit that is alive in sub-Saharan Africa can be harnessed to achieve this.

Since 2001, ICRISAT has arranged contract farming for seed production through a seed revolving fund supported by the United States Agency for International Development (USAID). To ensure quality, long-term training in seed production has been linked to seed revolving fund activities, through organizations such as the National Smallholder Farmers' Association of Malawi (NASFAM) and the Agricultural Seed Agency in Tanzania.

In eastern and southern Africa (ESA), six private seed companies (two in Malawi and four in Tanzania) have ventured into commercial seed production of legumes, targeting smallholder farmers with small (1–2 kg) seed packs.

In West and Central Africa, ICRISAT is supporting the development of local seed companies under the West Africa Seed Alliance. This aims to increase smallholder yields and incomes through the competitive and reliable provision of high quality affordable seed to smallholder

Farmers are looking for good and affordable seeds, a service that the seed systems can ensure

farmers. Working in partnership with the Citizen's Network for Foreign Affairs, the project focuses on the development of an agro-dealer network for input supply and output marketing. The Seed Science Center at Iowa State University is also collaborating in the project, with an emphasis on seed trade harmonization.

The impact

Currently the combined efforts of ICRISAT and national agricultural research systems provide 27 tons of the five popular released varieties in Malawi each season (about 5 tons of each). Until 2009 Pendo was the only popular variety in Tanzania and breeder seed production of this variety was spread across three major research stations and one farmer training center. Achievement of the target of at least 1 ton production per center has guaranteed 5 tons of Pendo breeder seed per year.

The ICRISAT seed revolving fund (SRF) for ESA, which has been in operation for the past 12 years, has met foundation and breeder seed requirements, producing approximately 185 tons of foundation seed and 12 tons of breeder seed per season. With additional funding from Irish Aid in 2009, the SRF increased its production to make seed available to the Government of Malawi's Farm Input Subsidy Program through a number of seed companies. Since 2005, using a contract system with large and smallholder farmer groups and collaborating partners, the ICRISAT SRF has produced about 707 tons of foundation seeds and 1,382 tons of certified seeds of five improved groundnut varieties released in Malawi. Within the same period, the fund also produced 197 tons of foundation seeds and 12 tons of seeds of four pigeonpea varieties released in Malawi.

In Tanzania, certified seed is produced by over 100 farmer groups, resulting in the production of 376 tons of certified groundnut seed since the project began. In Malawi, the system includes farmer clubs, farmer field schools and farmer marketing groups linked to NASFAM. Similarly, more than 2,808 tons of certified groundnut seeds have been produced in Malawi involving more than 450 farmers linked to the non-governmental organization CARE, 233 farmers linked to NASFAM, and

Many countries show encouraging levels of adoption of improved varieties, which can be enhanced by viable seed systems

73 farmers linked to the Millennium Villages Project, during the past 4 years of Tropical Legumes II project partnerships.

To ensure the efficient delivery of seed at low and affordable cost to end-users in West Africa, research institutions were tasked with producing breeder and foundation seed as part of the Groundnut Seed Project funded by the Common Fund for Commodities (2003–2007). This resulted in the production of more than 33 tons of breeder seed and 107 tons of foundation seed. In addition, community-based organizations produced more than 130 tons of certified seed and over 1,000 tons of Quality Declared Seed.

Through the project, 124 farmers' associations and 98 small farmers were trained in seed production technologies and small scale seed business skills, and were empowered in certified seed production and delivery schemes. When the project ended in 2007, some farmers' organizations, such as the women's association in Wakoro, Mali, voluntarily continued the scheme. Similarly in Niger, five women's associations in Hankoura and two women's associations in Faska were empowered in seed production and marketing of small seed packs.

Many countries show encouraging levels of adoption of improved varieties. In Mali, as a result of improved seed availability and accessibility for farmers, about 27% of the total area is planted with improved varieties. The adoption rate of improved varieties is estimated at 57% of the total area in Malawi, 35% in Tanzania, 59% in selected districts of Uganda, 57% in Zambia, and 22% of the total groundnut area in Nigeria. The reductions in unit costs of improved varieties range from 21% in Malawi to 44% in Uganda, compared to local varieties.

Seed systems enable poor farmers to access seed of improved varieties

Our **partners**

Accion Fraterna, Anantapur District, Andhra Pradesh, India
Acharya NG Ranga Agriculture University (ANGRAU), Hyderabad, India
Adriana Seed Company, Londrina, PR Londrina, Brazil
Advanced Research Institutes (ARIs) in participating countries
Agricultural Research Station (ARS), Gulbarga
Alliance for a Green Revolution in Africa (AGRA)
Andhra Pradesh State Seeds Development Corporation Ltd (APSSDC)
BAIF Development Research Foundation (formerly Bharatiya Agro Industries Foundation)
Beijing Genome Institute (BGI), Shenzhen, China
Beijing Genome Institute (BGI), USA
Bhopal Yuva Paryavaran & Sikshan Sansthan (BYPASS)
Biogene Agritech, Ahmedabad, Gujarat
Bioseeds Research India Pvt Ltd, Hyderabad, Andhra Pradesh
Chinese Academy of Agricultural Sciences (CAAS)
Cold Spring Harbor Laboratory, New York
Cooperative for American Relief Everywhere (CARE)
Conseil Ouest Africain pour la Recherche et le Développement Agricole/West and Central African Council for Agricultural Research and Development (CORAF/WECARD)
Central Research Institute for Dryland Agriculture (CRIDA), India
CGIAR Consortium
CGIAR Generation Challenge Programme (GCP)
Chaudhary Charan Singh Haryana Agricultural University (CCSHAU), Hisar, Haryana, India
Department of Agriculture, Andhra Pradesh, India
Department of Agriculture, India
Department of Agriculture, Thailand
Department of Agricultural Research, Myanmar
Department of Land Development (DoLD), Thailand
Dr Panjabrao Deshmukh Krishi Vidyapeeth (PDKV), Akola
Embrapa - Brazilian Agricultural Research Cooperation (Empresa Brasileira de Pesquisa Agropecuária)
Food and Agriculture Organization of the United Nations (FAO)
Global Crops Diversity Trust, Rome
IER – The Malian Institut d'Economie Rurale
Indian Council of Agricultural Research (ICAR)
Indian Institute of Pulses Research (IIPR), India
International Centre for Agricultural Research in the Dry Areas (ICARDA)
International Cooperation Centre for Agronomic Research for Development (CIRAD), France
International Fund for Agricultural Development (IFAD)
Institute for Agricultural Research, Nigeria
Institute of Grassland and Environmental Research, Aberystwyth
Institut National de l'Environment et des Recherches Agricoles (INERA), Burkina Faso
Institut Sénégalais de Recherches Agricoles, Senegal
Irish Aid
John Innes Centre, Norwich
Maharashtra Krishi Vidyapeeth (MKV), Parbhani
Maharashtra State Seeds Corporation (MSSC)
Millennium Villages Project
Monsanto Company
Myanmar Agriculture Service (MAS)
National Agricultural Research Systems (NARS) of participating countries
National Bureau of Plant Genetic Resources (NBPGR), India
National Center for Genome Resources, Santa Fe, New Mexico, USA
National Food Security Mission, India
National Seeds Corporation (NSC), India
National Smallholder Farmer Association of Malawi (NASFAM)
National University of Ireland, Galway
Nimbkar Seeds Pvt Ltd, Phaltan, Maharashtra
Non-government organizations (NGOs), local agricultural centers and farmer organizations in participating countries and regions
Selian Agricultural Research Institute (SARI), Ghana
SM Sehgal Foundation, Hyderabad
State Agricultural Universities (SAUs), India
State Farms Corporation of India Ltd (SFCI)
University of California, Davis
University of Copenhagen
University of Georgia
University of North Carolina
University of Wales, Bangor, UK
United States Agency for International Development (USAID)
Vibha Agrotech Ltd, Madhapur, HyderabadVietnam Academy of Agricultural Sciences (VAAS)

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Suhas Wani, Principal Scientist (Watersheds)

Appendix: **Crop list**

barnyard millet	*Echinochloa crus-galli* (L.) Beauv.
chickpea	*Cicer arietinum* L.
common bean	*Phaseolus vulgaris* L.
finger millet	*Eleusine coracana* (L.) Gaertn.
foxtail millet	*Setaria italica* (L.) P.Beauv.
groundnut	*Arachis hypogaea* L.
kodo millet	*Paspalum scrobiculatum* L.
little millet	*Panicum sumatrense* Roth ex Roem. & Schult.
maize	*Zea mays* L.
pearl millet	*Pennisetum glaucum* (L.) R.Br.
pigeonpea	*Cajanus cajan* (L.) Millsp.
proso millet	*Panicum miliaceum* L.
sorghum	*Sorghum bicolor* (L.) Moench
soybean	*Glycine max* (L.) Merr.

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