ANNUAL REPORT 2021

From Discovery to Scaling Up

CGIAR

CIMMYT[MR]

International Maize and Wheat Improvement Center

SUSTAINABLE DEVELOPMENT GOALS

On September 24, 2013, the newly formed United Nations (UN) High-level Political Forum on Sustainable Development held its first meeting. At the Rio+20 Conference, Member States also agreed to launch a process to develop a set of Sustainable Development Goals (SDGs), which were to build upon the Millennium Development Goals (MDGs) that were established in 2000 and expired in 2015.

Of the 17 individual goals, 10 relate directly to CGIAR activities and to CIMMYT's mandate. The SDGs have set the pathway for the next 15 years of agricultural, social, and economic development. Likewise, CGIAR has transformed its approach to ensure that its work aligns with the ambitious goals.

CIMMYT, through its research for development activities, is working toward a world free of poverty, hunger, and environmental degradation. CIMMYT and CGIAR efforts help bring the world closer to reaching the goals, such as the empowerment of women, the reduction of greenhouse gas emissions, and the improvement of health and nutrition for the world's poorest people.

CIMMYT's work contributes to the following SDGs:

ABOUT CIMMYT

The International Maize and Wheat Improvement Center (CIMMYT) is an international organization focused on non-profit agricultural research and training that empowers farmers through science and innovation to nourish the world in the midst of a climate crisis. Applying high-quality science and strong partnerships, CIMMYT works to achieve a world with healthier and more prosperous people, free from global food crises and with more resilient agri-food systems. CIMMYT's research brings enhanced productivity and better profits to farmers, mitigates the effects of the climate crisis, and reduces the environmental impact of agriculture.

CIMMYT is a member of CGIAR, a global research partnership for a food-secure future dedicated to reducing poverty, enhancing food and nutrition security, and improving natural resources.

For more information, visit cimmyt.org.

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MESSAGE from the Chair of the Board of Trustees

As I write this letter in the spring of 2022, I am looking at the world amid a "perfect storm" and contemplating the bold and accelerated actions we must take to face our present and the future with the required resolve.

The challenges facing the globe over the years continued to batter the world's farmers and consumers in 2021.

The COVID-19 global pandemic eroded hard-won gains in food and nutrition security, poverty reduction and gender equity, and showed signs of becoming a permanent fixture in our lives.

Despite efforts from the global community to reduce global warming, climate change is striking farmers – especially resource-poor smallholder farmers – with brutal drought, heat, and flooding.

And it is impossible to ignore the third part of this "perfect storm": the Ukraine-Russia crisis, and the resulting global food shortage, high food prices, hunger, and malnutrition – not to mention tragic loss of life and destruction – it is leaving in its wake.

Food security is critical to maintaining peace. Yet the actions and investments going into food security are not enough to drive the level of change required to prevent another catastrophe for the most vulnerable members of society. Key stakeholders, although united in this opinion, have not as of now followed through with concrete commitments to ensure that we turn the tide in humanity's favor.

The mission and work of CIMMYT have never been as critical as they are today.

I am incredibly proud of and humbled by the commitment of CIMMYT's staff and scientists, which has led to continuous research and partnership outcomes to empower millions of smallholder farmers through science and innovation.

CIMMYT staff and scientists know how to think globally and act locally and regionally to apply pragmatic tools to serve a global science program.

In just a few examples, the Accelerated Varietal Improvement and Seed Delivery of Legumes and Cereals in Africa (AVISA) project showed how CIMMYT's expertise and strong partnerships could translate to more farmers and additional crops: bean, cowpea, groundnut, millet, and sorghum. Likewise, CIMMYT's expertise in cutting-edge technology is expanding the use of biodiversity held in the world's genebanks to develop new climate-smart crop varieties for millions of small-scale farmers worldwide with the Allele Mining project.

2021 also marked a turning point in the reform of CGIAR, where CIMMYT has taken a valuable role in the development of the CGIAR 2030 Research and Innovation Strategy, aiming for impact in the face of the interdependent challenges facing today's world. Recently, the CGIAR System Board and System Council reviewed and approved the Investment Prospectus 2022–2024 and designated financing for 31 Initiatives, opening the door for CIMMYT scientists to propose new research initiatives with innovative and cross-cutting vision to delineate the future path of the organization's science while delivering impact at larger scales than ever before. I am excited to inform you that CIMMYT will participate directly in 21 of these new CGIAR Research Initiatives, and that 5 of them are headed or co-led by CIMMYT researchers.

CIMMYT has been able to reach these extraordinary achievements, despite financial hardship, with the greatly appreciated support of our funders. We are well aware that every dollar spent on overhead is a dollar less for our key stakeholder, the smallholder farmer. We are committed to working with CGIAR to streamline and simplify, with a clear focus on our talented scientists and staff in the fields and labs.

CIMMYT continues to provide the pragmatic tools and research methodology applied locally and regionally that, with the right actions and investments, will contribute to achieving the level of change required to prevent further catastrophic disruptions in the most vulnerable people's access to food.

CIMMYT's impact would not be possible without steady leadership. I am honored to take the role of Chair of CIMMYT's Board of Trustees, and to carry forward the important work of my predecessor, Nicole Birrell.

Our job is to make food security a right, not a privilege.

Margaret Bath

MESSAGE from the Director General

Welcome to CIMMYT's 2021 Annual Report!

Your reading of this document is evidence that you share our commitment to making a strong contribution to transform food systems on a global scale in this decisive decade for the United Nations 2030 Agenda of Sustainable Development Goals.

2021 was another challenging year because of subsequent COVID-19 waves. The global health emergency put the collective response capacity of the development sector to the test. It painfully raised awareness of the essential contribution that publicly funded research and capacity development efforts make to global peace and stability.

CIMMYT's mission, maize and wheat science for improved livelihoods, and our commitment to excellence in our operations and rapid response capacity are ever more important to help farmers, food workers and vulnerable communities avert a looming food crisis and mitigate the effects of the ongoing global health and food supply chain crises.

In this report, we summarize and highlight our progress on key areas of food systems transformation, including scientific discoveries, capacity building, technology transfer, and scaling efforts in the Global South.

Our research for development and capacity building work is closely aligned with and greatly contributes to the CGIAR Research and Innovation strategy, particularly to its five impact areas that aim to end hunger and malnutrition, alleviate poverty, bridge gender and youth gaps in agriculture, conserve biodiversity and natural resources, and adapt agriculture and mitigate its contribution to climate change.

Our 2021 report is organized in three sections or impact areas that are essential to food systems transformation, which means shifting the focus of global and local food production from efficiency to resilience, and from competition for resources to balance and inclusion.

To give you an overview of the contents of this report, on the discovery side we embarked on an ambitious initiative to apply environmental genome wide association methods to predict how today's maize, rice, sorghum, cassava, groundnut and bean varieties will perform, and to identify needed genetic diversity for them to succeed three or four decades from now. This is a very exciting area of research that will help us hedge our food systems against the harshest conditions anticipated from climate change, and an example of shifting the focus of our science from solving yesterday's problems tomorrow to solving tomorrow's problems today.

Breeding continues to be at the core of CIMMYT's excellence in science and response capacity. In 2021, we made great progress in boosting both maize and wheat's resilience to a hotter and drier world, but also to known and emerging biological threats in the form of ever evolving and invasive pests and diseases.

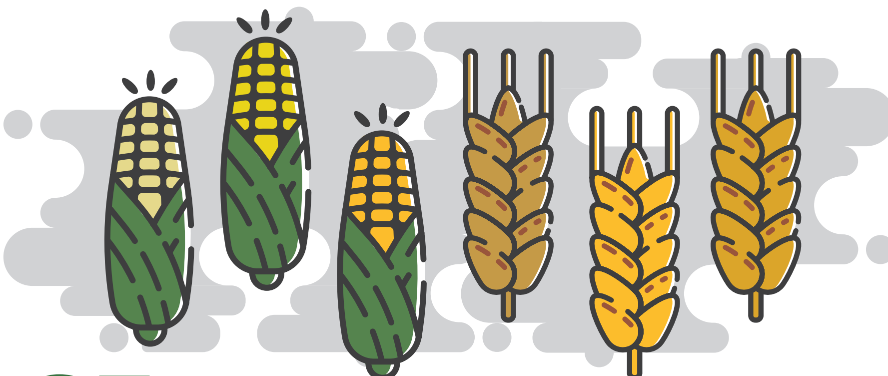
We also report on our progress scaling-up sustainable technologies and farming practices in the countries where we work in partnerships with dozens of public and private sector collaborators, and more importantly, with hundreds of thousands of farmers who put their trust in our unwavering determination to food systems transformation.

As I write these words, the world finds itself in front of an even more daunting challenge: a global food crisis fueled by conflict, trade disruptions, soaring commodity prices and climate change. Sadly, the world is not in the best position to address these converging threats. However, at CIMMYT we have solid, science-informed solutions, policy recommendations and proven methodologies that will help avert the global food security crisis that looms.

We are ready, conscious that there is no time to lose. Future generations will hold us accountable for our response to these immediate and long-term threats to humanity's food security and wellbeing. With your support we will rise, once again, to the occasion.

Bram Govaerts

2021 CIMMYT by the numbers



65 unique unique maize varieties and **70** unique wheat varieties resulting from our work.

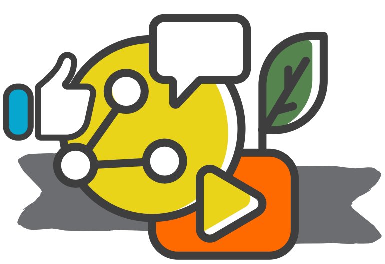
+458 maize and wheat seed shipments annually from our headquarters to more than **84 countries**, with at least **264K individual seed packets** in each shipment.

955K
pageviews on cimmyt.org.

433
peer-reviewed journal articles published.

+599K
downloads from our publications repository.

1,215 **staff of** **52** **nationalities.**



137K followers on social media and **140K video views** on YouTube.

40 **knowledge-sharing webinars** with our researchers and collaborators.

DISCOVERY AND VALIDATION

New endeavor FAST-TRACKS DISCOVERY OF USEFUL CROP DIVERSITY for climate resilience

The maize crops of many smallholder farmers like this one, in Hawassa Zuria District, Sidama Zone, Ethiopia, will increasingly suffer from high temperatures and erratic rainfall. New diversity from landraces can provide adaptive traits to improve crop breeding for such conditions, if landrace genome-environment associations can be characterized and used.

Researchers will source useful gene variations from CGIAR genebanks to develop climate-smart crops

A $25.7 million project led by CIMMYT with funding from the Bill & Melinda Gates Foundation is expediting the far-reaching use of the biodiversity held in the world's genebanks to develop new crop varieties for millions of small-scale farmers challenged by changing climates.

High temperatures, erratic rainfall, drought, flooding, and rising sea-levels from climate change are already depressing crop harvests and spreading hunger in millions of households worldwide.

To quickly and cost-effectively develop climate resilient varieties of cassava, cowpea, maize, rice, and sorghum – crops that underpin incomes and food security across Africa, Asia and Latin America – project partners are linking genetic and environmental data to find and deploy novel genetic variation from immense collections of seed and live cuttings of those crops.

Those collections are maintained, studied, and shared by CIMMYT and other Centers of CGIAR, the world's largest public sector agriculture research partnership, and represent among other things "landraces," which are heirloom varieties created and modified by farmers through selective planting over millennia.

> Use of new alleles has typically involved brute force field testing of many thousands of genebank samples, an approach that is difficult to scale, often inaccurate, and doesn't simplify the crossing of desired alleles into contemporary, elite breeding lines.
>
> Sarah Hearne

"CGIAR genebanks are humanity's premier source of new genetic variants, or 'alleles,' to breed for crop productivity and resilience against drought, diseases and other constraints," said Sarah Hearne, CIMMYT principal scientist and leader of the project. "Use of new alleles has typically involved brute-force field testing of many thousands of genebank samples, an approach that is difficult to scale, often inaccurate, and doesn't simplify the crossing of desired alleles into contemporary, elite breeding lines."

The advent of many new, low-cost molecular markers – DNA signposts for genetic segments that control physical traits in plants and animals – has

CGIAR Executive Managing Director Claudia Sadoff (left), learns more about CIMMYT's collection from Wheat Germplasm Bank Curator Carolina Sansaloni.

> We can also take data for future target environments – projecting what food crops are going to face in 10-20 years – and predict the genetic make-up of an ideal genotype, comprising collections of molecular markers for desired traits.
>
> Sarah Hearne

also brought rapid progress in genetic analyses of genebank collections. Coupled with greenhouse and field studies of actual plants, the analyses have identified landraces that bear promising genetic variation for drought and heat tolerance, but often with only an approximate idea of which landraces carry the novel alleles or where the alleles lie on the plant genome. One result is that progeny of landrace x elite crosses may carry a desired allele, but also large DNA segments linked to undesired traits that are difficult and expensive to cull.

To address this, the new project uses genebank seed samples' passport data, including when and where a sample was collected, to determine the environmental conditions (for example, frequent heat or drought around the crop's flowering period) that helped to shape a landrace's evolution. Selected environmental information and its presumed correlation to desirable plant types is combined with genetic data and all are used in analyses to discern associations between specific alleles and a favorable feature of plant performance, and to predict the overall potential performance of a landrace.

The outcomes include a better idea of the genomic location of potentially favorable new alleles and of the best landraces for further use in breeding.

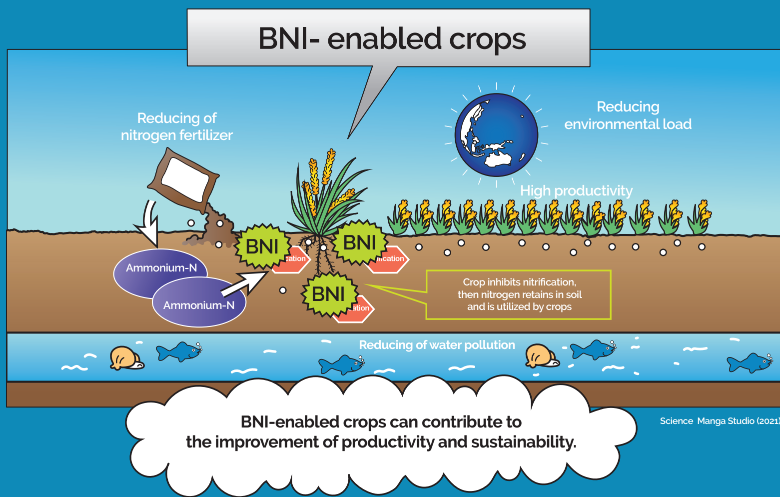
"We can also take data for future target environments – projecting what food crops are going to face in 10–20 years – and predict the genetic make-up of an ideal genotype, comprising collections of molecular markers for desired traits," Hearne explained.

"We then assess how nearly the landraces and even current elite varieties resemble the ideal genetically, allowing us to focus tightly our choices of breeding materials for a likely future."

This work builds on ten years of support to CIMMYT from the Mexican government, CGIAR Trust Fund contributors, and the Biotechnology and Biological Sciences Research Council (BBSRC) of the United Kingdom. The project is an "Innovation Sprint" coordinated by the Agriculture Innovation Mission for Climate (AIM4C) initiative, which is led by the United Arab Emirates and the United States, and part of the Crops of the Future Collaborative of the Foundation for Food & Agriculture Research (FFAR). Partners include the International Center for Tropical Agriculture (CIAT), the International Institute of Tropical Agriculture (IITA), the International Rice Research Institute (IRRI), Cornell University, Colorado State University, the University of California-Riverside, and the University of California-Davis.

NITROGEN-EFFICIENT WHEAT produces more food and less greenhouse gas

An international collaboration has transferred to elite wheat varieties a wild-grass chromosome segment that causes roots to secrete natural inhibitors of nitrification, offering a way to dial back on heavy fertilizer use for wheat and to reduce the crop's nitrogen leakage into waterways and air, while maintaining or raising its productivity and grain quality, said a report in the *Proceedings of the National Academy of Sciences* of the United States of America.



Growing wheat varieties endowed with the biological nitrification inhibition (BNI) trait could increase yields in both well-fertilized and nitrogen-poor soils, according to G.V. Subbarao, researcher at the Japan International Research Center for Agricultural Sciences (JIRCAS) and first author of the report.

"Nearly a fifth of the world's nitrogen-based fertilizer is deployed each year to grow wheat but – as with other major cereals, vegetables, and fruits – the crop takes up less than half of the nitrogen applied," said Subbarao.

Much of the remainder is either washed away, contaminating ground waters with nitrate and contributing to algae blooms in lakes and seas, or released into the air, often as nitrous oxide, a greenhouse gas 300 times more potent than carbon dioxide.

Using "wide crossing" techniques, Masahiro Kishii and other CIMMYT team members first transferred a BNI-linked chromosome region from the perennial grass species *Leymus racemosus* into a common wheat landrace and then into several elite CIMMYT wheat varieties, nearly doubling their BNI capacity, according to Hannes Karwat, a CIMMYT post-doctoral fellow and study co-author.

"Several responses in the plants' metabolism indicated a more balanced uptake of nitrogen," said Karwat, adding that the BNI-converted wheats also showed greater biomass and grain yield, with no loss of grain protein or breadmaking quality.

Under a project involving JIRCAS, the Indian Council of Agricultural Research (ICAR), and the Borlaug Institute for South Asia (BISA), BNI-converted wheat lines are being tested in India and the BNI trait transferred to popular national wheat varieties.

BNI research by CGIAR and JIRCAS is co-funded by the Ministry of Agriculture, Forestry and Fisheries of Japan.

CLASSIC MILPA MAIZE INTERCROPPING system feeds and nourishes marginalized communities

Traditional milpa intercrop – in which maize is grown together with beans, squash, and other crops – can furnish a vital supply of food and essential nutrients for marginalized, resource-poor communities in the Americas, according to a study published in *Nature Scientific Reports*.

One hectare of a milpa comprising maize, common beans, and potatoes can provide the annual carbohydrate needs of more than 13 adults, enough protein for nearly 10 adults, and adequate supplies of many vitamins and minerals. Based on data from nearly 1,000 households across 59 villages of the Western Highlands of Guatemala, the study is the first to relate milpa intercropping diversity with nutritional capacity, using multiple plots and crop combinations.

"Milpa production anchored around locally-adapted maize is still an essential food and nutritional lifeline for isolated, often indigenous communities throughout Mexico and Central America, and can be tailored to improve their food and nutritional security, along with that of small-scale farmers in similar settings," said Santiago López-Ridaura, a specialist in agricultural systems and climate change adaptation at CIMMYT and lead author of the article.

The Western Highlands of Guatemala is among the world's poorest regions – a mountainous area, ill-served by markets and where communities battered by food insecurity and malnutrition sow crops at altitudes of up to 3,200 meters, according to Cristian A. Reyna-Ramírez, a co-author of the study from the Universidad Autónoma Metropolitana-Xochimilco, Mexico.

A maize ear harvested from a "milpa," the maize-based intercrop that is a critical source of food and nutritional security for smallholder farming communities in remote areas such as the Western Highlands of Guatemala.

Natalia Palacios Rojas, CIMMYT maize quality and nutrition expert and a co-author of this article, notes that calculations of this and other milpa studies consider raw essential nutrients, and that research is needed on the nutritional contributions of cooked food and non-milpa foods such as poultry, livestock, home-garden produce, and purchased food – which, because most smallholder farm households that practice milpa agriculture have far less than a hectare of land, are essential supplementary food sources. Further work should also address the effects of storing milpa products on its nutrient stability and how the seasonal availability of milpa crops impacts diets and nutrition.

This work was funded by the United States Agency for International Development (USAID) as part of Feed the Future, the U.S. Government's global hunger, and food security initiative, under the Buena Milpa project, and supported by the CGIAR Research Program on Maize (MAIZE).

A VIEW from above

Adopting a different perspective, CIMMYT researchers are helping breeders advance crop improvement and farmers make better crop management decisions

CIMMYT scientist Francisco Pinto flies a drone during a presentation for government representatives at the experimental station in Ciudad Obregón, Sonora state, Mexico.

CIMMYT scientists have been using drones and other remote sensing tools to conduct high-throughput plant phenotyping, track pests and diseases, and detect land boundaries, as well as other applications for a while. But combining this technology with satellite imagery is proving to be game-changing.

With satellite imagery, scientists can replicate findings across farmers' fields. Integrating these two "bird's eye" technologies into decision support systems allows scientists, farmers and decision-makers to improve crops on a global scale at a low cost.

Measuring plant height with high-powered drones

In early 2021, scientists from CIMMYT, Brazil's Federal University of Viçosa and the private seed company KWS Momont Recherche successfully used drone technology to measure wheat crop height at four stages of growth. The scientists found that estimates gathered from drones were similar in accuracy to ground-based measurements.

Advancing assessment of pests and diseases

Drone imagery analysis enables scientists to make more objective disease severity assessments and speed up the development of disease-resistant maize varieties.

Using drone-based imaging, CIMMYT scientists and their research partners have improved the assessment of tar spot complex, found in Central and South America, and maize streak virus disease, present in sub-Saharan Africa.

Remote sensing experiments at test sites across Mexico have secured similar achievements with other common foliar wheat diseases, septoria and spot blotch.

Scientists have also been testing deep learning algorithms – computer algorithms that improve performance over time by adjusting to or "learning" from new data – to automate the assessment of leaf disease severity. This work, in partnership with the Federal University of Technology in Parana, Brazil, already suggests promising results.

CIMMYT scientists monitor a drone during a flying session.

Improving forecasts for crop disease early warning systems

In Ethiopia, a team from CIMMYT, the Catholic University of Louvain (UCLouvain), the University of Cambridge and the Ethiopian Institute of Agricultural Research (EIAR), are pioneering a world-leading wheat rust forecasting service using remote sensing solutions.

For farmers, wheat rusts can cause devastating losses in only a matter of weeks by destroying healthy wheat plants; early detection through warning systems is fundamental for prevention. The disease's potential existence can be predicted through a forecasting service, but the susceptibility of each plant to the disease is not yet known.

CIMMYT is trialling the use of drones and high-resolution satellite imagery to identify the presence of wheat rust and monitor the disease's progression, based on data from control field experiments and farmers' own fields.

With added expertise from the remote sensing lab at UCLouvain, the research team is now determining whether satellite data from the European Space Agency can aid mapping crop type distributions in Ethiopia.

Expert irrigation and sowing advice straight to farmers

Valuable data on irrigation scheduling and optimum sowing dates is now delivered directly to farmers in northern Mexico via the COMPASS smartphone app. The initiative, funded by the UK Space Agency, also enables farmers to assess weekly Normalized Difference Vegetation Index (NDVI) images of their fields and record their crop management activities.

Detecting field boundaries using high-resolution satellite imagery

Results from a study in Bangladesh found that innovative machine learning algorithms could detect the boundaries of agricultural fields based on high-resolution satellite images, which will help farmers with crop production and securing financial support.

Scientists from CIMMYT and the University of Buffalo used high-resolution satellite imagery to automatically create field boundaries. Knowing the size of their land helps farmers to access affordable credit to buy farm supplies and apply the correct amount of fertilizer to their land.

Developing climate-resilient wheat

Building on a decade of research, our wheat physiology team is implementing new high-throughput phenotyping approaches with the Heat and Drought Wheat Improvement Consortium (HeDWIC).

The team's work involves evaluating, validating and implementing remote sensing platforms for high-throughput phenotyping of physiological traits, ranging from canopy temperature to chlorophyll content, which indicates the greenness of a plant. High-throughput phenotyping requires quick and accurate phenotyping of many genotypes or plots.

These new approaches will assist in identifying and evaluating new adaptive traits for heat and drought in wheat. The team has also provided remote sensing data to improve genomic selection models for the Accelerating Genetic Gains in Maize and Wheat (AGG) project.

This work would not have been possible without the support of the Bill & Melinda Gates Foundation, the Biotechnology and Biological Sciences Research Council (BBSRC) of the United Kingdom, the Foundation for Food & Agricultural Research (FFAR), Mexico's Secretariat of Agriculture and Rural Development (SADER), and the United States Agency for International Development (USAID), who provided the needed funding.

An aerial view shows wheat trials at different stages of growth, at CIMMYT global headquarters in Texcoco, Mexico.

In search OF GENETIC DIVERSITY to fight climate change

National wheat breeding programs are getting a boost from an international partnership to mobilize diversity from genebanks for pest and climate resilience

Wheat wild relative *Aegilops variabilis* is regenerated under screenhouse conditions at CIMMYT, to have enough healthy and viable seed for distribution when necessary. This process is carried out every 20 years approximately.

Modern crop improvement practices have helped secure the world's wheat supply, but the growing threat of pathogens and environmental stressors could undo this achievement. Additional genetic diversity housed in genetic resource collections offers scientists the potential to adapt crops to these challenges.

As part of the Seeds of Discovery (SeeD) project, CIMMYT scientist Sukhwinder Singh led research on direct introgression of untapped diversity into elite wheat lines involving 15 international institutes across 8 countries to study how this can be done.

> Breeding wheat from a national perspective is a race against pathogens and other abiotic threats.
>
> Deepmala Sehgal

Mobilizing genebanks

Genebanks are a crucial piece of the puzzle. According to Singh, genebanks hold many diverse accessions of wheat landraces and wild species with beneficial traits, but until recently the entire breadth of diversity has never been explored and thousands of accessions have been "sitting on the shelves."

Building on research undertaken through the SeeD project, which genetically characterized nearly 80,000 samples of wheat from the seed banks of CIMMYT and the International Center for Agricultural Research in the Dry Areas (ICARDA), Singh and colleagues collected vast and detailed data on diversity within genebanks, and developed a faster way to put it to use for variety development.

The research targets beneficial traits in these accessions through genome mapping, passing them to breeding programs around the world.

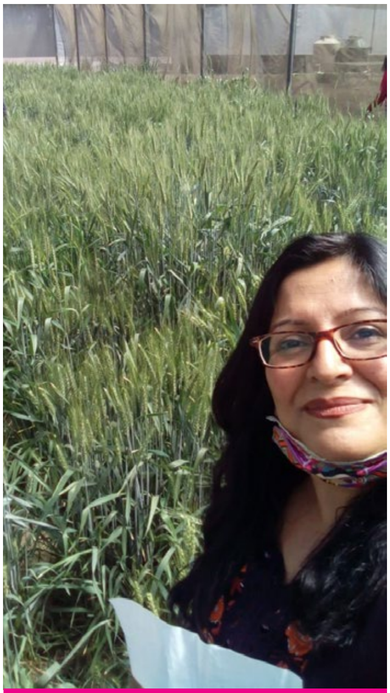
First, the team undertook a large meta-survey of genetic resources from wild wheat accessions held in genebanks, to create a catalogue of improved traits and identify a subset of diverse accessions. Next, they developed a strategic three-way crossing method among 366 genebank accessions and the best historical elite varieties to reduce the time between the original introduction and deployment of an improved variety.

A race against time

Introducing beneficial genes from genetic resources into elite cultivars demands substantial resources, such as time and money, that national programs do not always have in abundance.

"Breeding wheat from a national perspective is a race against pathogens and other abiotic threats," said Deepmala Sehgal, wheat geneticist at CIMMYT.

The outcomes from CIMMYT's research help ease this burden. A diverse array of new germplasm, resulting from crosses of genebank accessions with elite varieties made through the SeeD project is currently used by national breeding programs – such as in India, Kenya, Mexico and Pakistan – to make new crosses or evaluate the germplasm in yield trials in their own environments. Overall, national breeding programs have adopted 95 lines for their targeted breeding programs and 7 lines are currently undergoing varietal trials. Lines developed in Mexico showed increased resistance to abiotic



Scientist Deepmala Sehgal multiplying Linked Topcross Population (LTP) lines.

Regeneration of *Aegilops* spp. at CIMMYT.

Regeneration of *Aegilops neglecta* at CIMMYT.

stresses. In Pakistan, lines tested exhibited increased disease resistance; and in India, many tested lines are now part of the national cultivar release system.

International collaboration takes action

At CIMMYT, many of the developed lines carrying groupings of genetic variants, known as haplotypes, are being used in trait pipelines to introduce these novel genomic regions into advanced elite lines. CIMMYT researchers are collaborating with physiologists to dissect any underlying physiological mechanisms associated with the research team's findings.

"Through the haplotypes-based analysis in the pre-breeding germplasm, we identified exotic genome footprints in bread wheat, and efforts are underway to mobilize the research outputs in breeding pipelines," Sehgal said. "This work has also delivered pre-breeding lines to trait pipelines within national breeding programs."

International collaborations play a crucial role in preserving crop diversity, bringing out successful products and, sharing new methods and knowledge.

This work would not have been possible without the support of the Government of Mexico, through the MasAgro Biodiversidad project, the CGIAR Research Program on Wheat (WHEAT), and the Biotechnology and Biological Sciences Research Council (BBSRC) of the United Kingdom, who provided the needed funding for extensive multi-location trials.

STUDY UNCOVERS NEW GENETIC resources for wheat disease resistance in Kazakhstan

A genome-wide association study of more than 190 spring and winter wheat lines and varieties by CIMMYT and Kazakhstan scientists identified wheat chromosome segments that give the crop genetic resistance to two damaging races of tan spot, a foliar disease that can cut wheat harvests in half.

Caused by the fungus *Pyrenophora tritici-repentis*, tan spot increasingly threatens wheat in Central Asia and particularly Kazakhstan, a major exporter of wheat grain to northern Africa, Central Asia, and Europe.

"Bread wheat is the most important crop in Central Asia, and is directly linked to food security; 45–60% of inhabitants' daily calories come from wheat," said Alma Kokhmetova, professor and head of the Genetics and Breeding Laboratory at the Institute of Plant Biology and Biotechnology (IPBB), Kazakhstan.

Water scarcity limits wheat yields in Kazakhstan. Average annual precipitation in key wheat areas just barely meets the crop's needs and a severe and prolonged drought has reduced harvests as much as 18%. To help capture and retain moisture from rains and snow, farmers on over two million of Kazakhstan's 15 million hectares of wheat land practice zero tillage: sowing seed directly into unplowed soils and residues from previous crops.

Unfortunately, the tan spot fungus thrives in crop straw left on these unplowed soils. Rather than abandon climate smart-farming practices, farmers can control the fungus by rotating the wheat with non-susceptible crops, removing or plowing over crop residues, and using fungicides.

Evaluation of tan spot disease resistance in a greenhouse.

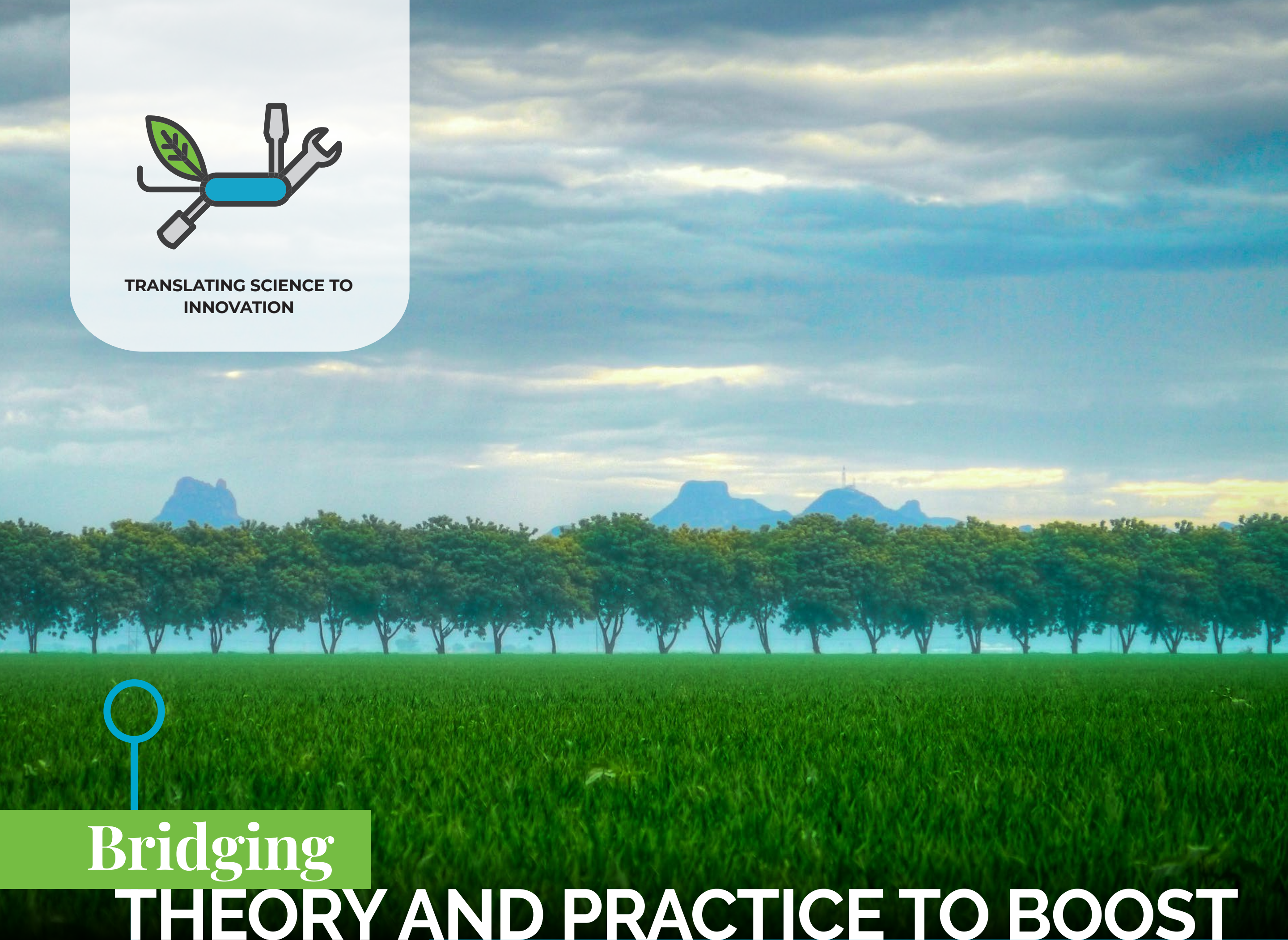
The best solution, however, is wheat that possesses genetic resistance.

Genome-wide association studies focus on millions of single-nucleotide polymorphisms in the wheat genome, allowing scientists to "dissect" the genetic architecture of traits such as disease resistance and to identify new genes or beneficial versions of known genes. This study included breeding lines from Kazakhstan and wheat samples from Brazil, Russia, CIMMYT, and the International Winter Wheat Improvement Program.

Using the study findings, the scientists identified 25 wheat lines that offer allelic combinations for resistance to the two most damaging races of tan spot fungus in Kazakhstan.

This work was funded by the Kazakhstan Ministry of Education and Sciences. Technical support of IPBB Laboratory staff was greatly appreciated.

TRANSLATING SCIENCE TO INNOVATION



Bridging THEORY AND PRACTICE TO BOOST climate resilience

Norman E. Borlaug Experimental Station in Ciudad Obregón, Sonora state, Mexico.

Scientists accelerate the climate resilience of staple crops, by integrating proven breeding methods with cutting-edge technologies

As the past eight years have been the warmest on record and global temperatures are predicted to rise by as much as two degrees Celsius over preindustrial levels by 2050, the world's food crops are increasingly under threat.

A review published in the *Journal of Experimental Botany* describes how researchers from CIMMYT and collaborators are boosting climate resilience in wheat using powerful remote sensing tools, genomics, and big data analysis. Scientists are combining multiple approaches to explore untapped diversity among wheat genetic resources and help select better parents and progeny in breeding.

> An advantage of understanding abiotic stress at the level of plant physiology is that many of the same tools and methods can be applied across a range of crops that face similar problems.
>
> Matthew Reynolds

The review – authored by a team of 25 scientists from CIMMYT, Henan Agricultural University, the University of Adelaide, and the Wheat Initiative – also outlines how this research can be harnessed on a global level to further accelerate climate resilience in staple crops.

"An advantage of understanding abiotic stress at the level of plant physiology is that many of the same tools and methods can be applied across a range of crops that face similar problems," confirmed the first author and CIMMYT Wheat Physiologist, Matthew Reynolds. Abiotic stresses such as temperature extremes and drought can have devastating impacts on plant growth and yields, posing a massive risk to food security.

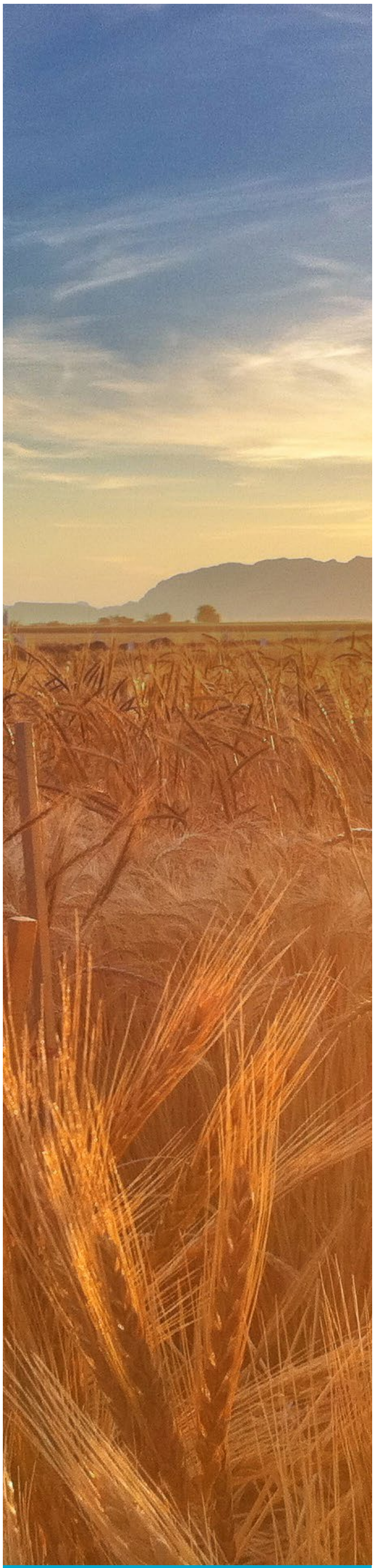
Addressing research gaps

The authors identified nine key research gaps in efforts to boost climate resilience in wheat, among them a need to better identify future breeding targets, limited genetic diversity for climate resilience, smarter strategies for stacking traits, and addressing the bottleneck between discovery research in basic plant science and its application in breeding.

Based on a combination of the latest research advances and tried-and-tested breeding methods, scientists are developing strategies to address these gaps. These include:

- Using big data analysis to better understand stress profiles in target environments and design wheat lines with appropriate heat and drought adaptive traits.
- Exploring wheat genetic resources to discover novel climate-resilience traits and genes for use in breeding.
- Accelerating genetic gains through crossing and selection techniques that encompass the latest tools in phenomics with genomics.
- Crowd-sourcing new ideas and technologies from academia and testing them in real-life breeding situations.

These strategies are being thoroughly tested at the Heat and Drought Wheat Improvement Network (HeDWIC) Hub in Mexico under realistic breeding conditions before being disseminated to other public and private wheat breeding programs around the world facing similar challenges. One factor that strongly influences the success and acceleration of



Norman E. Borlaug Experimental Station in Ciudad Obregón, Sonora state, Mexico.

climate resilience technologies, according to Reynolds, is the gap between theoretical discovery research and crop improvement in the field.

"Many great ideas on how to improve climate resilience of crops pile up in the literature, but often remain 'on the shelf' because the research space between theory and practice falls between the radar of academia on the one hand, and that of plant breeders on the other," Reynolds explained.

Translational research – efforts to convert basic research knowledge about plants into practical applications in crop improvement – represents a link between the world of fundamental discovery and farmers' fields, bridging this gap.

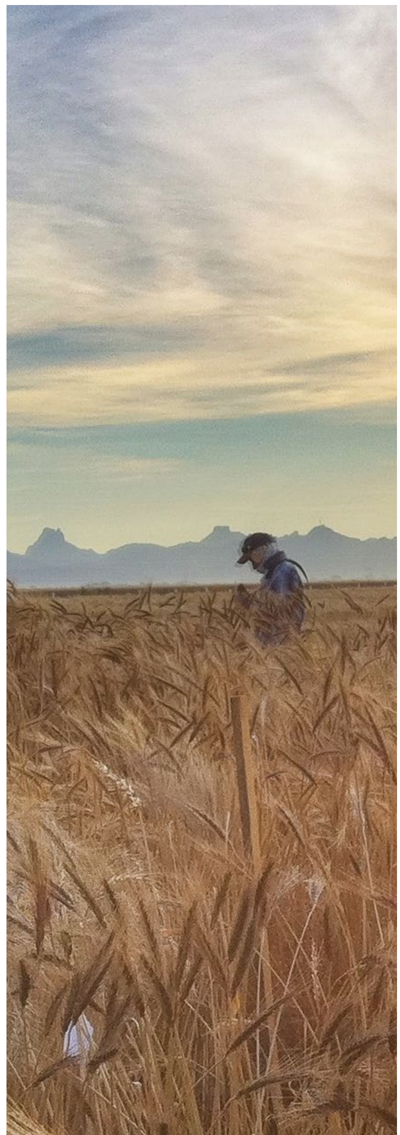
The impacts of this research, conducted by HeDWIC – a project led by CIMMYT in partnership with experts around the world – will be validated on a global scale through the International Wheat Improvement Network (IWIN) and the International Winter Wheat Improvement Program (IWWIP), with the potential to reach the most public and private wheat breeders globally.

The results will benefit breeders and researchers and, most importantly, farmers and consumers around the world who rely on wheat for their livelihoods and their diets. Wheat accounts for about 20% of all human calories and protein, making it a pillar of food security. For about 1.5 billion resource-poor people, wheat is their main daily staple food.

> Many great ideas on how to improve climate-resilience of crops pile up in the literature, but often remain 'on the shelf' because the research space between theory and practice falls between the radar of academia on the one hand, and that of plant breeders on the other.
>
> Matthew Reynolds

With the world population projected to rise to almost ten billion by 2050, greater demand for food is inevitable. This is especially so for wheat, being a versatile crop both in terms of where it can grow and its many culinary and industrial uses. However, current wheat yield gains will not meet 2050 demand unless serious action is taken. Translational research and application of new scientific discoveries into breeding are crucial elements in ensuring that research outputs are converted into higher and stable yielding and resilient varieties to support farmers, and agriculture, to meet these challenges.

This work would not have been possible without the support of the Foundation for Food and Agricultural Research (FFAR), the United States Agency for International Development (USAID), the Biotechnology and Biological Sciences Research Council (BBSRC) of the United Kingdom, the Mexican Ministry for Agriculture, the Accelerating Genetic Gains in Maize and Wheat (AGG) project, and the CGIAR Research Program on Wheat (WHEAT).



Norman E. Borlaug Experimental Station in Ciudad Obregón, Sonora state, Mexico.

Plant genetics and the FUTURE OF FOOD SECURITY in sub-Saharan Africa

Powerful genetic tools and technologies accelerate maize improvement

Over the past century, science-based plant breeding has played a key role in safeguarding global food security and continues to be a mainstay of CIMMYT's work to improve livelihoods and foster more productive sustainable maize and wheat farming in low- and middle-income countries.

Each year crop breeders and scientists around the world monitor genetic trends – patterns in crop improvement in their breeding programs. By monitoring these trends, scientists can look back and measure the rate of genetic gain to see how effective their breeding programs are. The consensus among experts is that effective breeding programs can and should achieve at least 1% genetic gains in their breeding programs and ideally 1.5–2% per year.

Doubled haploid technology shortens the breeding cycle significantly by rapid development of completely homozygous lines (in two or three generations),instead of the conventional inbred line development process, which takes at least six generations to derive lines with ~99% homozygosity.

A field worker at CIMMYT's experimental station in Agua Fría, in Mexico's state of Puebla.

A mixture of doubled haploid maize kernels seen in close-up at CIMMYT's Agua Fría experimental station in Mexico.

In 2021, CIMMYT scientists estimated the genetic trends for CIMMYT's eastern and southern Africa maize breeding programs, using data from the last ten years to provide a baseline for each breeding program.

The results showed that most of the breeding programs are meeting the targeted 1–1.5% genetic gain each year, demonstrating that CIMMYT's maize breeding programs are effective.

With the help of international partners, CIMMYT scientists also worked to get improved maize seeds to market – to boost farmers' resilience to climate change and to emerging pests and diseases. In 2021, CIMMYT scientists produced over 170,000 tons of certified stress-tolerant maize seeds, covering around 7 million hectares of land in sub-Saharan Africa. This reached an estimated 7.2 million households and benefited 44 million people in sub-Saharan Africa.

In collaboration with the Excellence in Breeding (EiB) platform, CIMMYT scientists worked to define, test in combination, and mainstream genetic tools, approaches and technologies to improve the effectiveness of their breeding programs. Focusing on shortening the breeding cycle time and improving selection of the best varieties from generation to generation, the team looked at combinations of doubled haploid technology, marker-assisted breeding, genomic selection and statistical indexing methods.

Doubled haploid technology shortens the time it takes to develop a potential new variety from four years to one. This not only saves time and money, but also allows breeders to redirect resources to evaluating more candidate varieties or "finalists."

At CIMMYT's doubled haploid facility in Kenya, partners in Ethiopia, Kenya, Mozambique, Uganda, Zambia, and Zimbabwe submitted 40 maize populations to the facility and an estimated 4,000 doubled haploid lines will be delivered to them in 2022.

Marker-assisted breeding is another tool in a CIMMYT breeder's belt. Using DNA markers associated with desirable traits, breeders can select plants early in the breeding process saving time and money. CIMMYT scientists have been using this technology to select lines with resistance to maize lethal necrosis, a viral disease that appeared in eastern Africa in 2011 and quickly spread to attack maize crops across the region. Accelerating the development of maize that is resistant to this disease is an important step to protecting smallholder farmers from losing their harvests and safeguarding food security.

Accelerating maize improvement through statistics

CIMMYT scientists carried out computer simulations of the maize breeding program to understand how reducing the maize breeding cycle time might improve genetic gain. They found that identifying new breeding parents earlier in the breeding process could increase the genetic gain by 9% compared to identification at later stages of testing. Based on these results they were able to cut the breeding cycle length from five years to four years, meaning huge cost and time savings for maize improvement.

Genomic selection takes advantage of low-cost, genome-wide molecular markers to analyze large populations and allow scientists to predict the value of particular breeding lines and crosses to accelerate gains, especially for improving genetically complex traits. CIMMYT scientists and partners compared genomic selection and phenotypic selection of maize in sub-Saharan Africa and found that both methods performed equally well across optimum and drought conditions. Overall, genomic selection is conducted at two thirds of the cost of phenotypic selection, showing that it is an important strategy for making crop improvement more cost efficient.

Finding the best way to carry out selection simultaneously on multiple traits is a challenge for all plant breeders.

The Experimental Station Ernest W. Sprague in Agua Fría, Mexico, is used for the doubled haploid process. Its location promotes an assemblage of aggressive insect pests and disease pathogens, making it an ideal location to study crop response to biotic stresses.

To further improve this process, EiB and CIMMYT scientists used "selection indices" to better select new parents in the maize programs. The team estimated the heritability and available genetic variation for each trait, together with the correlations between these traits. Putting these estimates into an interactive software package, breeders were able to visualize the trade-offs associated with different traits, balancing the relative amount of gain desired for each trait within the constraints of the breeding population. The output is an overall genetic merit score for each family from a breeding population, which is used to select the parents of the next cycle of breeding.

With challenges like climate change and pests and diseases continuing to threaten food security and livelihoods, getting high-performing, resilient crop varieties to farmers quickly and efficiently is paramount.

With more than 60% of the population in sub-Saharan Africa involved in agriculture, most of which are smallholder farmers, finding and testing the best combination of genetic tools and technologies to boost agricultural productivity and resilience is a key strategy to lift the region out of poverty and reduce hunger.

This work would not have been possible without the support of the Bill & Melinda Gates Foundation, the Foundation for Food and Agriculture Research (FFAR) and the United States Agency for International Development (USAID), who provided the needed funding for the Accelerating Genetic Gains (AGG) project.

The science BEHIND THE PERFECT bread and pasta flour

Next time you visit a store or restaurant, consider how many items contain wheat. Through analysis of advanced wheat lines, CIMMYT is enabling production of nutritious and affordable wheat-derived food in developing countries, and maximizing profits for those involved at each stage of the development chain.

Wheat contributes around 20% of the total energy and protein intake to diets worldwide through thousands of different products. Due to each wheat line's unique characteristics and processing requirements, the type of wheat used changes depending on the end product.

At CIMMYT's Wheat Quality laboratory, scientists analyze the nutritional, processing and end-use quality for thousands of wheat lines each year. The aim is to achieve quality grain and flour for the wheat products consumed and produced in CIMMYT partner countries.

The bread wheat quality characterization process begins by analyzing grain weight, density, protein content, moisture content and hardness in order to test the overall grain quality.

Wheat flour and freshly baked bread.

Next, grains are milled into flour and analyzed for a second time. Scientists examine their moisture content, protein content and color.

At this stage, CIMMYT undertakes multiple tests to analyze the protein quality of the grain, which is integral for determining the end-use for the flour. This work is specifically important for bread wheat flours, which are first analyzed for their overall protein quality and gluten strength, an important element for processing. Analysis of the mixing characteristics in flour is achieved using mixographs, while the dough properties of elasticity and extensibility are measured through alveographs.

Depending on the end-use target for the grain, the flour is then analyzed for its suitability to produce a specific product. Bread wheat flours are typically used for baking using yeast, so the lab scores different loaves based on their volume and crumb quality.

The quality characterization is also crucial for durum wheat, which is often used to make Italian-style pasta. Durum wheat samples are analyzed for their grain quality, flour yellowness, protein content and protein quality, using the SDS-sedimentation volume test.

This work would not have been possible without the support of our partners and the CGIAR Research Program on Wheat (WHEAT).

Anayeli Morales and her colleagues at CIMMYT's Wheat Quality lab evaluate how different bread wheat varieties behave at the time of baking.

A lab technician determines the sedimentation volume of different wheat flour samples. Larger sedimentation volumes indicate stronger gluten.

FROM DAILY WAGE LABORERS to resilient farmers

Whether as farmers, wage earners or entrepreneurs, women are the backbone of the rural economy, especially in developing countries. In addition to caring for their families and domestic chores, rural women are actively involved in producing food crops and looking after livestock. In regions like South Asia, where more than two thirds of employed women work in agriculture, they are the human link between the farm and the table.

And yet, despite being key drivers of growth and poverty reduction, their contribution to farming often remains unrecognized.

Over the last years, recognizing and promoting women's value in countries like Bangladesh, India, and Nepal has triggered a significant change in the perception of women's roles in agriculture. Once considered daily wage laborers, women working in the fields are now increasingly perceived as resilient and enterprising farmers, and as critical partners to improve family income and ensure food security in rural communities.

Through the Cereal Systems Initiative for South Asia (CSISA), CIMMYT has been at the forefront of empowering women in South Asia, strengthening their capacities and enhancing their economic and social status. In addition to training them on small-scale mechanization and key grain quality parameters, CIMMYT provided them with market access to agricultural value chains and fostered collaboration among women's self-help groups, farmers' producer groups, private seed companies, and other collectives.

Wheat-based systems in the Indo-Gangetic Plains are becoming increasingly "feminized" as women take on more farm work, responsibilities, and decision-making roles. In Bangladesh, for instance, women's participation in agriculture continues to increase as off-farm opportunities decline. In countries like Nepal and Pakistan, with men migrating for work, women are becoming de-facto heads of households and making more decisions around farming.

A farmer holds maize ears in a field in India's state of Odisha.

Even though some of these trends are common in many countries, avoiding generalizations is critical to ensure that feminization processes are positive forces in maize and wheat systems. Not only do social norms vary across borders, but intersectionalities between gender, caste, and other identities can strongly impact women's meaningful participation in farming. A CIMMYT-published policy guidance, "Supporting labor and managerial feminization processes in wheat in the Indo-Gangetic Plains: A guidance note," shines a brighter light on the role of women in wheat-based farming systems in the region and provides actionable recommendations to researchers, rural advisory services, development partners, and policymakers on how to support working communities more effectively and knowledgeably. Engaging with local partners, including women's groups and NGOs, is also crucial to develop gender-transformative approaches that engage and benefit vulnerable and marginalized communities for lasting solutions.

This work would not have been possible without the support of our partners United States Agency for International Development (USAID), the Bill and Melinda Gates Foundation, the International Development Research Centre (IDRC), the CGIAR Gender Platform, and the CGIAR Research Program on Wheat (WHEAT).

SCALING UP INNOVATION: TAKING IT TO THE FARMER AND SOCIETY

Lowering NITROUS OXIDE emissions? There's a map for that

CIMMYT scientists map global hotspots for nitrous oxide emissions from maize and wheat production, setting a clear path for emissions reduction efforts

A farmer in Ethiopia prepares to spread urea fertilizer by hand in his field after the sowing of wheat.

Like many issues besetting agrifood systems today, the question of nitrogen use appears to yield contradictory problems and solutions depending on how and where you look. Many parts of the globe are experiencing environmental consequences due to excessive nitrogen application while, in other parts, agricultural productivity is severely affected by low nitrogen.

Maize and wheat systems are at the heart of this dilemma, as they account for around 35% of global nitrogen fertilizer usage and play a critical role in ensuring the food security of a growing population.

> Spatially explicit quantification of N_2O emission and mitigation potential helps identify emission hotspots and priority areas for mitigation action, through better nitrogen management, consistent with location-specific production and environmental goals.
>
> Tek Sapkota

Addressing this issue means ensuring that nitrogen is applied with maximum efficiency across the world's croplands. Farmers should be applying only as much nitrogen as can be taken up by their crops. Apply more, and the excess nitrogen is lost to the environment in different forms, including nitrous oxide (N_2O) emissions – a potent greenhouse gas. Apply less, and agricultural potential goes unmet.

Given the twin challenges of global climate change and the projected need to increase global food production over 70% by 2050, neither scenario is desirable.

Tackling the problem first requires an accurate accounting of N_2O emissions from global maize and wheat fields, followed by quantification of the potential for farmers to mitigate nitrogen emissions, disaggregated by region. In 2021, scientists at CIMMYT, in conjunction with researchers at the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), accomplished this important step in a study published in *Science of the Total Environment*.

"Spatially explicit quantification of N_2O emission and mitigation potential helps identify emission hotspots and priority areas for mitigation action, through better nitrogen management, consistent with location-specific production and environmental goals," said Tek Sapkota, CIMMYT's climate change science group lead and review editor of the Intergovernmental Panel on Climate Change (IPCC)'s sixth assessment report.

A girl prepares wheat seeds for sowing in Ethiopia.

Quantifying greenhouse gas

CIMMYT scientists and partners quantified N_2O emissions using four statistical models, which were validated against actual measurements recorded at 777 globally distributed points.

They found that, for both maize and wheat, emissions were highest in East and South Asia, as well as parts of Europe and North America. For maize, parts of South America also appeared to be emissions hotspots. In Asia, China, India, Indonesia and the Philippines were major emitters for both crops. Researchers also observed that China, along with Egypt, Pakistan and northern India have the highest excess nitrogen application.

Trimming the excess

Specifically identifying hotspots of excess nitrogen application is important, as they represent promising areas to target for emissions reductions. For a given region, the volume of emissions may be a factor

A farmer sows wheat by hand in Ethiopia.

of large maize or wheat cultivation areas, coupled with high levels of nitrogen usage. Farmers may not have much room to reduce nitrogen application without affecting their yield – and reducing the area under cultivation may not be desirable or viable. Where the rate of excess nitrogen application is high, however, reducing the rate of application and increasing the efficiency of nitrogen use is a win-win.

The researchers estimate that a nitrous oxide emission reduction potential of 25-75% can be achieved through various management practices, such as the 4Rs, which stand for the right source, right timing, right placement, and right application rate. The case for emissions reduction potential of 4R management practices was bolstered by a meta-analysis also published in 2021 by a team of scientists that included CIMMYT researchers.

Not only would such a reduction drastically reduce N_2O emissions and lessen other environmental impacts of maize and wheat production, but it would also represent significant cost savings to farmers. Improved efficiency in nitrogen application can also have positive effects on crop yield.

"Promoting integrated nitrogen management approaches through the right policies, institutional support and good extension systems is essential to improving the use efficiency of nitrogen in order to meet food security, climate action and other sustainable development goals," Sapkota said.

Kindie Tesfaye, a CIMMYT scientist and lead author of the mapping study, commented on its policy importance. "The estimated mitigation potentials from global maize and wheat fields are useful for hotspot countries to target fertilizer and crop management as one of the mitigation options in their Nationally Determined Contributions (NDCs) to the United Nations Framework Convention on Climate Change (UNFCCC)."

This work would not have been possible without the support of our partner, the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), which provided the needed funding.

Two decades of MAIZE IMPROVEMENT in sub-Saharan Africa

CGIAR maize varieties have become prominent in the region, helping smallholder farmers develop their knowledge to increase yield

"We learned about techniques like spacing and understanding the potential yields of the different varieties," said Mary Sikirwayi, a maize farmer from Rimbi village, Murewa district, Zimbabwe, who took part in maize on-farm trials conducted by CIMMYT.

Sikirwayi's story is one of many to emerge from two decades of longstanding, CGIAR-led work on improved maize for sub-Saharan Africa, summarized in a comprehensive review titled "Impacts of CGIAR Maize Improvement in sub-Saharan Africa, 1995-2015."

This study reports on the adoption and impacts of CGIAR-related maize varieties in a selection of major maize-producing countries in sub-Saharan Africa from 1995 to 2015.

Farmer Abduraman Tuku harvests green maize for his cattle in Shonda village, Arsi Negele, Ethiopia.

> When it comes to growing maize, I now consider myself an expert because of the knowledge I have. I have a sustainable livelihood from farming maize, my grandchildren can go to school with the income of maize sales, they have enough to eat, and we no longer have hunger in our home.
>
> Mary Sikirwayi

Focusing on 18 African countries, the study shows that around 60% of the 1,345 maize varieties released had a known or reported CGIAR parentage.

By 2015, about 34% of the total maize area in the 18 countries, representing 9.5 million hectares, was cultivated with relatively new CGIAR-related maize varieties (released between 1995 and 2015), while another 13% of the region's total maize area was cultivated with CGIAR-related maize varieties released before 1995.

Countries targeted for this study were categorized based on their area under maize cultivation into "large producers" (eight countries averaging more than one million hectares of maize per year during 1995 to 2015) and "small producers" (ten countries with less than one million hectares).

The share of released maize varieties with CGIAR genetics was found to be similar across both groups of countries. However, among the large producers, several varieties were based on crosses between CGIAR and non-CGIAR maize germplasm; this equates to 24% of all released varieties, compared to 10% in the small producer group. A more active private seed sector and stronger domestic breeding capacity within the large producers is the likely cause of this difference.

For both producer categories, varietal releases with a CGIAR relationship were released more quickly than non-CGIAR varieties. This was particularly pronounced during the study's final five years, when 304 varieties with a CGIAR relationship were released compared to 60 non-CGIAR varieties. Stepping up CGIAR maize breeding activities and strengthening regional networks since the mid-1990s may have contributed to this pattern.

Farmers Sagulani (right) and Bamusi Stambuli show their storage full of maize ears of drought-tolerant variety ZM 309, in Balaka, Malawi.

Farm worker Justa Eliudi detassels maize for seed production at Suba Agro's Mbezi farm in Tanzania.

Exciting germplasm releases include those resistant to major diseases, such as maize streak virus, gray leaf spot, maize lethal necrosis, and those tolerant to drought and low soil fertility.

The farmer demand for traits such as these is reflected in the findings: even in countries that released a few varieties each year relative to their maize growing area – called a low varietal release "intensity" – the share of CGIAR-related maize varieties was a substantial 87%.

CIMMYT scientists discovered a strong association between the seed type – hybrids versus open-pollinated varieties – and CGIAR involvement in varietal development.

A large proportion (73%) of maize varieties released in the region during the study timeframe were hybrids; they accounted for 65% of all CGIAR-related releases and 88% of non-CGIAR releases.

Many of these hybrids were submitted for registration and subsequent commercialization by small seed companies.

For open-pollinated varieties, which typically have cheaper seed than hybrids, a vast majority (84%) had a CGIAR relationship.

The research incorporated economic analysis of maize improvement for sub-Saharan Africa. In 2015, the aggregate yearly economic benefits of using newer CGIAR-related maize varieties (released after 1994) were estimated to be between $0.66-1.05 billion. Compared to the benefits, global investment in CGIAR maize improvement was modest. At its peak, yearly investment reached about $30 million.

The report's data is collected from an expert survey among maize breeders in CGIAR and partner institutions, and secondary sources and publications.

This work would not have been possible without the support of our partners Bill & Melinda Gates Foundation, United States Agency for International Development (USAID), and funding agencies that supported the CGIAR Research Program on Maize (MAIZE) who provided the needed funding.

A field worker weighs maize at CIMMYT's experimental station in Tlaltizapán, Mexico.

Design THINKING for sustainable futures

New planning methodology can support global food systems transformation

The success of food systems across the world is severely limited by long-term challenges, like yield gaps and climate vulnerability. However, research-based solutions – in public policy, agricultural value chains, and finance – are often constrained by short-termism and zero-sum thinking.

To better respond to current and emerging challenges, decision makers need to switch the focus to multi-sector, evidence-based collaboration.

To aid this process, a multi-disciplinary team of agricultural researchers and development practitioners have proposed a new approach to tackling the shortcomings of global food production systems. Developed by CIMMYT scientists in collaboration with the Alliance of Bioversity International and the International Center

> CIMMYT's integrated development approach to maize systems transformation in Mexico and Colombia laid the foundations of the IASI methodology by overcoming government transitions, annual budget constraints and win-or-lose rivalry between stakeholders in favor of equity, profitability, resilience and sustainability.
>
> Bram Govaerts

for Tropical Agriculture (the Alliance), the Integrated Agri-Food System Initiative (IASI) methodology aims to transform national food systems by using design thinking – which means understanding specific needs to define innovative solutions – to achieve consensus between varied stakeholders.

The team developed the IASI model based on the successful implementation of CIMMYT's integrated development projects in Colombia and Mexico, which focused on working with actors in the public, private and civil sectors to enhance local maize systems. These initiatives capitalized on social and political windows of opportunity that helped build stakeholder consensus around health, nutrition, food security and development aspirations.

In both countries, the IASI focus on drivers of change helped broaden lists of potential solutions and more effectively embed new strategies within government institutions, thereby increasing the likelihood of impact and continuity across successive political regimes. In Mexico, for example, the process led to the creation of a tactical plan for improving agricultural production systems by translating innovation networks into knowledge co-creation hubs. These include research, demonstration modules, and extension areas where members of the local community can help test, improve, and adapt sustainable farming practices and technologies, and provide a foundation for continuous scaling.

"CIMMYT's integrated development approach to maize systems transformation in Mexico and Colombia laid the foundations of the IASI methodology by overcoming government transitions, annual budget constraints and win-or-lose rivalry between stakeholders in favor of equity, profitability, resilience and sustainability," said CIMMYT Director General a.i. Bram Govaerts.

Ultimately, the IASI approach offers public officials and development practitioners a means of transforming food systems by scaling out innovative farming practices and technologies that lead to sustainably managed natural resources and improved nutrition and food security.

How it works

According to a paper published in 2021, the first step for applying the IASI methodology is to identify windows of opportunity. These will vary across different national contexts, and might arise with political transitions, fiscal crises, shifts in trade conditions for key commodities, or new donor initiatives – in short, the times when influential actors are re-evaluating their goals and how to reach them, and are therefore more likely to entertain new approaches and information sources.

Once the opportunity has been identified, there are six major steps to applying the IASI methodology. First, experts must examine the current status and the business-as-usual scenario based on analysis of the socioeconomic, political, and sectoral context and model-based projections. At the same time, stakeholders determine a preferred future scenario based on assessment of national implications and define the key drivers of change.

Field workers weed maize plots at CIMMYT's experimental station in Agua Fría, Mexico.

Defined criteria are then applied to these stakeholder and expert inputs to validate drivers of change and identify strategies and actions that can steer toward the desired future scenario. These could include, for example, public policies, value chain and market interventions, or biotechnology applications, which would be reviewed and prioritized by high-level decision makers.

Stakeholders then agree on measurable targets and tangible, time-bound actions towards the preferred future scenario, and build shared commitments to a tactical implementation plan in collaboration with partners. Ongoing stakeholder engagement would be organized around an online dashboard that tracks actions and progress towards targets, while also supporting course correction and coordinated investment. By following these steps, the creators of the IASI methodology propose the construction of a "global food systems transformation network" to help co-design and co-implement agricultural development projects that bring together multiple partners and donors for global agricultural systems transformation.

As the approach is refined and further applications are built, they expect that this network will harness efforts to initiate a new field of research and global practice on "integrated methodologies for food system transformation and innovation" – analogous to the fields of business administration and organizational development.

IASI serves as the backbone of the new CGIAR Regional Integrated Initiatives, which draw on capacities from regional international agricultural research centers and programs to deliver global agrifood system transformation.

This work would not have been possible without the support of our partners, Alliance of Bioversity International and CIAT and CGIAR.

STRESS-RESILIENT HYBRIDS HELP maize farmers in tropical rainfed conditions in Africa and Asia

Droughts, high temperatures, and fall armyworm are recurring **stresses** for maize farmers in Africa and Asia, but stress-tolerant maize varieties and integrated pest management can protect both crop yields and the livelihoods of smallholders.

Heat-tolerant hybrids developed and deployed in India

Small-scale maize farmers grappling with erratic rainfall in Karnataka, India, who adopted a new drought- and heat-tolerant maize hybrid are harvesting nearly one ton more grain per hectare than those who planted stress-vulnerable varieties.

Climate-resilient hybrid RCRMH2 was developed in 2015 by CIMMYT and deployed in partnership with the University of Agriculture Sciences, Raichur (UAS-R), Karnataka, under the Heat Tolerant Maize for Asia (HTMA) project.

“This hybrid is a boon for our stress-prone areas, as it gives guaranteed yields in a bad year,” said Hanumanthappa, a farmer and adopter of the variety in Gadag District. “Not only can it feed my family, but also my cattle,” he added, as the leaves and stems can be used for livestock fodder thanks to the hybrid’s “stay-green” trait.

A 2018–19 survey of farmers in Gadag District with poor rainfall and in Dharwad District with good rainfall, released in 2021, found that farmers there who grew the hybrid harvested 0.96 tons more grain and earned $190 per hectare more than neighbors who did not adopt the hybrid.

The crop also produced larger kernels than other hybrids under drought conditions, bringing a better sale price to farmers.

Nepal’s National Maize Research Program (NMRP) and CIMMYT scientists with Lumbini Seeds staff at their hybrid seed production plot in Bairawah, Nepal.

Fall armyworm management in Africa and Asia

Host plant resistance is an important component of integrated pest management of fall armyworm, which continues to be a major threat to maize-dependent farmers in Africa and Asia. In the last five years, CIMMYT’s team in Africa identified three maize hybrids with tolerance to fall armyworm, which are licensed to national partners in 12 countries and undergoing national performance trials.

Published in 2021, “Fall Armyworm in Asia: A Guide for Integrated Pest Management” emphasizes an intensive, science-based response strategy to mitigate the fall armyworm challenge. “While the publication is focused on Asia, it provides an updated understanding of various components of fall armyworm integrated pest management that could also benefit stakeholders in Africa,” said B.M. Prasanna, Director of CIMMYT’s Global Maize Program and CGIAR Research Program on Maize.

CIMMYT’s work on fall armyworm management received funding support from the CGIAR Research Program on Maize (MAIZE) and the United States Agency for International Development (USAID) Feed the Future initiative.

BUILDING UP BUSINESSES to boost agricultural mechanization

When it comes to agricultural mechanization, developing new technologies is only one part of the equation. Machinery businesses need to market their products, and farmers must be able to easily access and use them. In 2021, CIMMYT researchers from Bangladesh to Zimbabwe worked to foster linkages between farmers, machinery manufacturers and distributors, and agricultural service providers, in a bid to ensure that farming communities around the world can benefit from new technologies.

In Bangladesh, CIMMYT scientists supported agricultural industries in Cox's Bazar – a district in the southeastern area of the country bordering Myanmar – by increasing private sector capacity to develop, manufacture and market mechanized fodder choppers.

Access to these machines drastically reduces the laborious and time-consuming process of chopping plant matter to feed livestock. On average, a farmer can hand-chop 500kg of forage or fodder each day, while the machines can process around 1,000kg per hour.

While the machines can save farmers around $7 in daily labor costs, uptake in the area was low, as the remoteness of the region made it difficult for farming communities to learn about and access the machines. To counter this, CIMMYT partnered with international development nonprofit ACDI/VOCA – through the Livestock Production for Improved Nutrition (LPIN) Activity, funded by the United States Agency for International Development (USAID) – to connect local farmers and agricultural service providers with chopper producers and distributors, as well as to provide training on machine operation.

The initiative proved extremely successful, with 25 choppers purchased locally to meet continued demand for fodder from dairy farms across the region.

In June 2021 the initiative received an award from USAID, in recognition of outstanding collaboration to increase agricultural mechanization in communities hosting Rohingya refugees from nearby Myanmar.

Farmers watch a demonstration on how to use a reaper in Bangladesh.

Building relationships

In addition to making new technologies more readily available, in 2021 CIMMYT also invested in existing relationships with local agricultural mechanization businesses.

In Meki, Ethiopia, Beyene Chufamo is reaping the benefits. After training as a mechanic through a CIMMYT initiative supported by the German development agency GIZ, in 2019 he set up a successful workshop specializing in maintenance, repair and overhaul services for two-wheel tractors. In 2021, his continued association with CIMMYT connected him with newly established machinery leasing businesses, allowing him to increase his earnings significantly.

Currently, Beyene helps maintain the smooth operation of machinery and equipment at CIMMYT project sites in Amhara, Oromia and Tigray, which involves everything from training other local mechanics and troubleshooting for service providers, to facilitating the delivery of aftersales services in project areas. In 2021 he had 91 service providers as regular clients at CIMMYT project sites – up from just 19 in 2016.

This work would not have been possible without the support of our partners, including ACDI/VOCA, Deutsche Gesellschaft fuer Internationale Zusammernarbeit (GIZ), Ethiopia's Ministry of Agriculture, the Ethiopian Institute of Agricultural Research (EIAR), Georgia Institute of Technology, iDE, Livestock Production for Improved Nutrition (LPIN), and the United States Agency for International Development (USAID) who provided support for the initiatives described above.

Mechanization experts promote two-wheel tractors and other scale-appropriate machinery at a seed pop-up market in Zimbabwe.

TOP FUNDERS 2021

(in thousands of U.S. dollars, based on 2021 research execution)

FUNDER	AMOUNT
CGIAR Research Programs and Platforms (see Note 1)	40,249
Bill & Melinda Gates Foundation	23,026
United States Agency for International Development (USAID)	18,119
Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH	5,122
Mexican Government Contributions (see Note 2)	4,753
Foundation for Food and Agriculture Research (FFAR)	1,723
Walmart Foundation	1,199
World Food Programme (WFP)	1,095
Ministry of Agriculture and Farmers Welfare, India	888
Global Crop Diversity Trust	780

(amounts exclude deferred depreciation)

Note 1: Australia, Belgium, Bill & Melinda Gates Foundation, Canada, France, Germany, Global Crop Diversity Trust, India, Ireland, Japan, New Zealand, Republic of Korea, The Netherlands, Norway, Sweden, Switzerland, Thailand, United Kingdom (FCDO), United States Agency for International Development (USAID) and World Bank.

Note 2: Includes federal and local state contributions. Out of the 2021 fund contribution committed by the Government of Mexico, as of August 2022, $4.3 million is pending disbursement.

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African Agricultural Technology Foundation (AATF)

ARVALIS - Institut du végétal

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Biotechnology and Biological Sciences Research Council (BBSRC), United Kingdom

Borlaug Institute for South Asia (BISA)

Centre for Agricultural Bioscience International (CABI)

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Chinese Academy of Agricultural Sciences (CAAS)

Commonwealth Scientific and Industrial Research Organisation (CSIRO)

Context Global Development (CGD)

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Development Fund, Norway

Digital Green Foundation

Driscoll's Operaciones, S.A. de C.V.

Food and Agriculture Organization of the United Nations (FAO)

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Grupo Trimex, PepsiCo

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Ministry of Foreign Affairs (MOFA), Japan

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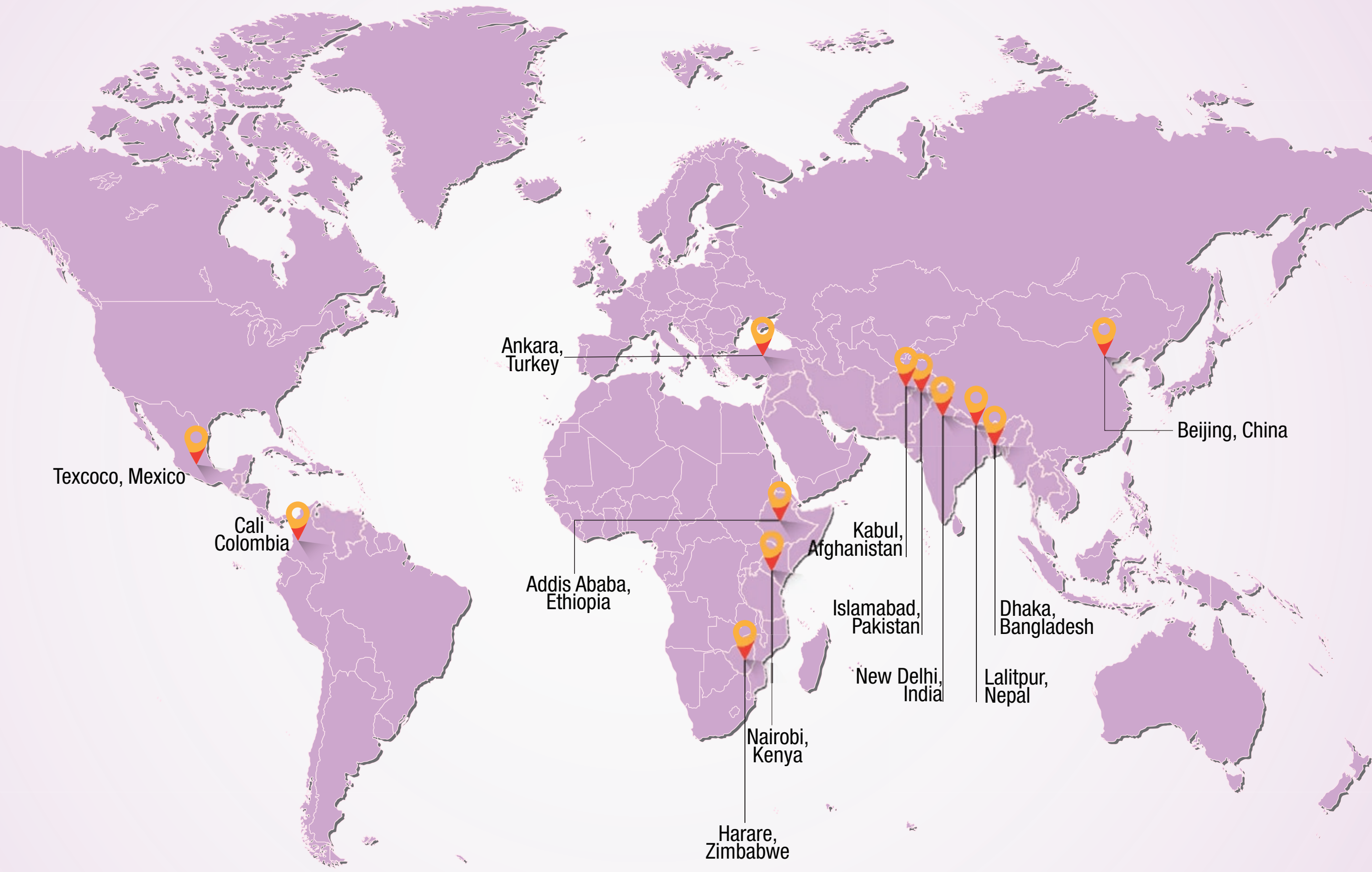

ACRONYMS

ACDI/VOCA	Agricultural Cooperative Development International/ Volunteers in Overseas Cooperative Assistance
AGG	Accelerating Genetic Gains in Maize and Wheat project
AIM4C	Agriculture Innovation Mission for Climate initiative
AVISA	Accelerated Varietal Improvement and Seed Delivery of Legumes and Cereals in Africa project
BBSRC	Biotechnology and Biological Sciences Research Council of the United Kingdom
BISA	Borlaug Institute for South Asia
BNI	Biological nitrification inhibition
CCAFS	CGIAR Research Program on Climate Change, Agriculture and Food Security
CGIAR	(Formerly the *Consultative Group for International Agricultural Research*)
CIAT	International Center for Tropical Agriculture (*Centro Internacional de Agricultura Tropical*)
CIMMYT	International Maize and Wheat Improvement Center (*Centro Internacional de Mejoramiento de Maíz y Trigo*)
COVID-19	Coronavirus Disease 2019
CSISA	Cereal Systems Initiative for South Asia
DNA	DeoxyriboNucleic Acid
EIAR	Ethiopian Institute of Agricultural Research
FFAR	Foundation for Food & Agriculture Research
GIZ	German Agency for International Cooperation (*Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH*)
HTMA	Heat Tolerant Maize for Asia project
IASI	Integrated Agri-Food System Initiative methodology
ICAR	Indian Council of Agricultural Research
ICARDA	International Center for Agricultural Research in the Dry Areas
IDRC	International Development Research Centre
IITA	International Institute of Tropical Agriculture
IPBB	Institute of Plant Biology and Biotechnology, Kazakhstan
IPCC	Intergovernmental Panel on Climate Change
IRRI	International Rice Research Institute
IWIN	International Wheat Improvement Network
IWWIP	International Winter Wheat Improvement Program
JIRCAS	Japan International Research Center for Agricultural Sciences
LPIN	Livestock Production for Improved Nutrition activity
LTP	Linked Topcross Population
MAIZE	CGIAR Research Program on Maize
N_2O	Nitrous oxide
NDVI	Normalized Difference Vegetation Index
NMRP	National Maize Research Program, Nepal
SADER	Mexico's Secretariat of Agriculture and Rural Development (*Secretaría de Agricultura y Desarrollo Rural*)
SDS	Sodium dodecyl sulfate
UAS-R	University of Agriculture Sciences, Raichur
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USAID	United States Agency for International Development
WHEAT	CGIAR Research Program on Wheat

Unless otherwise indicated, all currencies are expressed in U.S. dollars.

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