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THE ROLE AND CONTRIBUTION OF PLANT BREEDING AND PLANT BIOTECHNOLOGY TO SUSTAINABLE AGRICULTURE IN AFRICA

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Africa's economy is driven by agriculture, a sector that constitutes 32% of the continent's GDP. The ongoing Agricultural Transformation Agenda (ATA) in Africa hinges on a system change (from subsistence farming to agribusiness) approach that explores high productivity to strengthen the African economy. During the "Green Revolution" period, increased global yields of cereal crops were achieved through the interactions of breeding and agronomy. However, in the face of current challenges, such as climate change and need for new market niches, there is an increasing exigency to explore modern plant breeding (including biotechnology) to develop new varieties with the capacity for high yields in reduced chemical-input systems and with the genetic diversity needed to maintain yield stability in Africa´s fluctuating climatic conditions. Biotechnology has significantly shortened the time required for the development of new cultivars, varieties and hybrids. Modern breeding tools include Double Haploid technology, marker assisted breeding, genomics, genetic engineering and genome editing. It is these tools that help accelerate the development of market responsive varieties needed for sustainable agriculture in Africa that will be highlighted.

KEY WORDS: TECHNOLOGY, CROP IMPROVEMENT, GENETICS, MODERN BREEDING TOOLS.

Introduction

Africa's economy is driven by agriculture, a sector that generates one-third of the national income and accounts for 70-80% of the labor force in the continent. Although Africa is endowed with immense natural agricultural resources, the continent is still hampered by low agricultural productivity and food insecurity. The yield per unit area of crops grown in Africa is globally the lowest compared with the other regions of the world. Due to low levels of productivity and other interrelated constraints, an estimated 40 percent of people in Sub-Saharan Africa (SSA) live below the poverty line (UNEP 2002: 16). So, low productivity coupled with unparalleled population increase has contributed to the prevailing food insecurity in the continent. The fact that 85-90% of SSA's agriculture is rain-fed, indicates that climate-change effects can only have aggravated the already dire situation. Concomitantly, climate change increases child malnutrition and drastically reduces calorie consumption. Thus, aggressive agricultural productivity investments are needed to raise calorie consumption to levels sufficient to off-set the negative impacts of climate change on the health and well-being of children (Nelson et al. 2009).

Low productivity in Africa has increased the continent´s dependence on food produced in other parts of the world. For instance, rice imports have multiplied more than eight-fold since 1960. Hard earned scarce currency in Africa is ploughed back into food imports. This exposes the African population to the risk of fluctuating food prices on international markets which is unsustainable. Food challenges in Africa are not just about insufficient production, availability, and intake, but also include other mounting concerns related to food safety and nutrition. To compound these challenges, Africa has the lowest levels of technological, institutional and financial resources with which to address the problems (UNEP 2002).

In line with the challenges mentioned above, Africa must therefore improve its productivity by 2050 when the population is projected to double, and this in a difficult context of land that is becoming less arable and the need to secure water supplies without adverse impact on the natural environment. If the present and future food needs of the continent are to be addressed adequately, further investment in agricultural management and technology will be crucial to generate a 70% increase in food production by 2050 (Delaney, 2015:132-143). Investment in crop improvement technologies have largely been considered by breeders as crucial to rapidly manipulating the process of developing new super yielding varieties required to close current food gaps in Africa. In the last 30 years advances in plant breeding and biotechnology have allowed a range of possible novel applications (Awais *et al.*, 2010:210-220).

A complete transformation of the agricultural clime for a growing continent essentially demands a comprehensive upgrade of its crop improvement structure to integrate and explore advanced technologies for the innovtive development of the next generation of crop varieties that are resilient to the impact of climate change. Such varieties must exhibit compelling attributes such as high/good yields and other demand driven commercial traits that fit with rapidly expanding market profiles of the 21st century at local and international levels. In this regard, in recent years several initiatives have been undertaken in Africa through a series of investments to strengthen research for genetic improvement, product development pipeline and delivery systems required to guarantee sustainable food and nutrition security. Plant breeding as an old science has been explored over decades in Africa and is currently being leveraged by the rapid integration of new technologies including biotechnology that see further advances in crop improvement. With respect to the latter, the African Agricultural Technology Foundation (AATF) has been at the forefront of transformation in agriculture to explore technologies to drive food security for Africa.

This paper, therefore, highlights the key innovative interventions and other regional developments that are rapidly guiding the transformation process of African agriculture, namely: 1. the contribution of plant breeding and biotechnology to Africa's food and nutrition, 2. AATF's contribution to access, adaptation, delivery and stewardship of technologies for small holder farmer (SHF) benefits and 3. the paradigm shift to agri-business as a tool to accomplish SDG goals especially with respect to reducing poverty, ensuring food security, fighting hunger and promoting an eco-friendly management of natural resources.

Advances in crop improvement from classical breeding to the use of biotechnology tools

Conventional/classical breeding

Traditional plant breeding which depends on phenotypic selection has been historically applied for effective crop improvement and development in Africa. Several classical breeding methods have been developed in the last century, an are used globally. Africa has utilized the most widely used and successful methods for crop improvement. Thus, most crop varieties released in Africa were developed via classical breeding. Under recent initiatives, one of the most successful crops released is the (New Rice for Africa (NERICA) series which is made up of derivatives of the interspecific lines from the crosses between the African cultivated species of rice (*Oryza glaberrima*) and the Asian cultivated species (*Oryza sativa*) developed by Africa Rice Center (AfricaRice). Harvest Plus have also used classical breeding to develop nutritionally enhanced crops (e.g. potato, rice, cassava etc.,).

The initial breeding efforts in Africa focused mainly on yield and component traits. However, this soon shifted to quality traits for farmer preferences to enhance adoption with a view to improving markets, as the emphasis shifted to industrial traits. The breeding programs have evolved over time to identify new traits beyond yields, diseases and pest resistance, including screening for rare traits in the collections. Ideally, the new novel traits that are being targeted to benefit a truly sustainable agriculture in Africa include improved seed biology, abiotic and biotic stress tolerance/resistance, crop resource use efficiency, and new market-driven post-harvest/industrial qualities. The threat of climate change meand that current trends are laying stronger emphasis on the development of climate resilient crops (Figure 1). Among the classical breeding approaches that have been exploited in Africa include germplasm assemblage and population improvement, recurrent selection, generation of genetic stocks and hybrid development through heterosis.

Germplasm assemblage and population improvement — Genetic diversity provides variations of alleles that are suited to breeding elite lines for adaptation to changing environments, plant fitness and other traits of breeding interest. A narrow genetic base is an important limiting factor undermining population improvement, and it is a major bottleneck in many breeding programs in Africa. Thus, the creation of genetic variation through germplasm collections locally and introductions into Africa from centers of origins have beenpivotal in the development of many breeding programs in many countries. Such collections form the basic foundation upon which crop improvements in Africa are sustainably anchored on (Varaprasad and Sivaraj, 2010:1276-1293).

Massive germplasms have been built in Africa and it is expected to continue to expand to meet the dynamic changes of human needs and the ever-growing economic opportunities for cash and commercial crops.

Recurrent selection — Recurrent selection has been used to improve yield and genetic gain with huge successes. It involves the reselection of generation after generation, with the intermating of selected plants to produce the population for the next cycle of selection. This approach basically improves the mean performance of a population of plants while maintaining the genetic variability within the target population to permit continual progress from selection. It is easier to use in cross-pollinating crops and has been successfully used for a large number of crops. It has contributed much the effective manipulation and improvement of rather complex traits given the high number of genes associated with it as well as improving the frequency of useful alleles in a population. As more traits are combined in a single genotype this approach has emerged as being very useful. Breeding progress via this strategy depends on the heritability of the trait targeted for selection, the types of gene action considered important in controlling it, the relative efficiency of selection, and the complexity of the trait under selection. Several crops driving food security such as cereals, legumes and root crops have benefitted from the use of this breeding method in Africa. For example maize, cassava and other staple crops in Africa have been improved through recurrent selection.

Generation of genetic stocks — Genetic stocks represent a unique and extremely valuable germplasm which, depending on crop, type of genetic stock and user community, may represent genetic resources of either transient or long-lasting value. Genetic stocks principally include cytological stocks (e.g. chromosome addition/substitution, aneuploids), mutants (e.g. induced/insertion mutants) and germplasm sets (e.g. parental lines), inbreds, haploids and test lines. Members of either of these groups have found their relevance in plant breeding. These stocks, where biologically developed, are very useful in accelerating breeding and understanding the genetics of the traits.

Highly improved genetic stocks have been generated and/or selected for genetic studies and for use in the development of improved elite lines. While many genetic stocks have been developed, sustainable maintenance has been challenging in national programs due to insufficient facilities. Some crops have biological constraints that restrict the availability of some genetic stocks. For example, while haploids have been successfully used in maize, this has yet to be achieved withn cassava where inbreds are still not available. Alongside the advances in modern breeding, parental lines for specific or novel traits of interest have been identified and selected for use in crosses for trait introgression and allele mining from plant genetic resources and/or genetic stocks towards the development of new and improved high yielding superior genotypes or varieties (Gokidi et al. 2017: 167-180). More investment in the development of genetic stocks is still required in Africa to enhance breeder's capacity in genetic improvement for traits that are more appropriately suited to Africa's food, nutrition and market demands.

Hybrid development through Heterosis — The phenomenon of heterosis has been extensively explored for enhanced plant performance and is one of the most successfully applied principles in commercial plant breeding. It is based on an approach that explores a specific pair of 2 heterotic groups that express high hybrid performance (heterosis) when crossed. The identification of heterotic groups is principally determined through pedigree, quantitative and geographic analyses. The delineation of germplasm into useful heterotic groups are very useful in guiding breeders to utilize their germplasm in a more efficient and consistent manner through exploitation of complementary lines for maximizing the outcomes of a hybrid breeding program. Such heterotic groups are explored to guide inbred line developments which are used as parents (which often come from two genetically distant heterotic groups) for further development of hybrid varieties (Meena et al. 2017, 61-73). This breeding method has been widely used for yield improvement and has been found attractive by the private sector for the business incentives it offers since they hold the property rights of the parents. Special skills are required for the use of the inbred line parents in developing hybrids efficiently. Maize is one of the most successful crops that has benefited from this method. It has been used both in national, international and private breeding programs in Africa. Its application has been most widespread in East and Southern Africa where there is the highest concentration of maize seed companies (Badu-Apraku and Fakorede 2017: 111 – 137).

Limitations of classical breeding

In spite of the major successes of classical breeding programs, the processes are time-consuming and labor-intensive - it typically takes 8-10 years to develop and release a variety and could take even more time where a crop´s biological constraints are more daunting. A good example is when the traits of interest are controlled by multiple genes that are difficult to manipulate. Understanding the genetic basis of complex traits and the pyramiding of favorable alleles for native traits are the building blocks of new opportunities for crop improvement (Bliss, 2007: S250-S261; Varshney et al., 2012: 1172-1176) for the 21st century. Unfortunately, these are not easily amenable to classical breeding approaches. In a traditional breeding context there are severe limitations in terms of genetic resource conservation, the development of heterotic pools for hybridization, the cleaning of genetic stocks to remove viruses, pre-breeding to knock off genetic load, screening for allelic variants of traits, the rapid multiplication of vegetatively propagated crops, the slow pace of introgression of useful traits from landraces and from unrelated and related species into elite materials. Other challenges include gene mining from wild species, long breeding cycles, novel trait creation where unavailable in crop germplasm, the slow pace of genetic gain and quality trait improvement.

These limitations and the need to explore ways to expedite crop improvement processes have resulted in the need to explore new paradigms of genetic improvement offered by biotechnology. Massive investment in biotechnology has resulted in several new breeding tools that have rapidly brought a new dimension to the science of variety development and deep insights into genetics. Biotechnology has rapidly modernized breeding in the world, and while there has been some progress in its integration into research and development pipelines for products in Africa, it has been more successfully used in other continents.

Biotechnology as next generation tools for crop improvement

Biotechnology is the application of scientific techniques to modify and improve plants, animals, and micro-organisms to enhance their value. It offers an opportunity to guide and sustain the crosses and the screening of the progeny and can contribute to the introduction of new markers and traits, which cannot easily be crossed in a natural sense. Thus, biotechnology has been pivotal in a new breeding age that has brought a new concept to crop improvement. Biotechnology through molecular breeding has emerged not only as a strong tool for speeding up the process but also for enhancing understanding of the fundamental life processes in genetics at the cellular and molecular levels. Thus, advances in biotechnology that address the limitations of classical breeding have resulted in the development of tools/techniques (Table 1), that strongly complement classical breeding. Among the tools are tissue culture (for embryo rescue, rapid generation of disease-free stock (e.g. micro-propagation of vegetatively-propagated staple crops, such as cassava, potato, sweet potato, taro bananas and plantains), diagnostic tools (for pathogen testing and disease indexing), doubled haploid technology (for rapid attainment of homozygosity in hybrid development), molecular markers (for trait selection in breeding, trait introgression, diversity analysis etc.), genomics (gene function, performance prediction, complex trait dissection), omics (Physiological, biosynthetic and metabolic pathways); genetic engineering (gene transfer among non-related species); and gene editing (specific site directed mutagenesis). An abundant array of advanced biotechnology tools is now being applied to enhance our understanding of genes, genome, transcriptional analysis and development of ideotypes of novel genotypes. Breeding has benefited largely from these biotechnology applications which have resulted in huge agricultural transformation and these approaches are being widely explored globally and rapidly being integrated into processes of crop improvement in Africa.

Doubled Haploid (DH) — DH is one of the most revolutionary developments that has transformed and fast-tracked inbred line development and reduced number of years required to produce a hybrid line. A doubled haploid (DH) genotype is generated when haploid cells (particularly, maternal haploid cells) are induced *in vivo* to undergo chromosome doubling through Colchicine treatment. DH technology is important in plant breeding - plant breeders generate pure lines in a single generation, which may save considerable time in the breeding of new cultivars. The application of DH technology reduces the time for inbred line development to 1 or 2 generations (Prigge et al., 2011: 1498-1506) compared to classical pedigree methods that produce 96.9 % homozygous lines after 6 to 10 generations of selfing heterozygous material (Hallauer et al., 2010). Not many countries have facilities to support this technology in Africa, but it has been explored through collaborative partnership with advanced international centers. In Sub-Saharan Africa, a DH technology facility was established in Kiboko, Kenya in 2012 through the Water Efficient Maize in Africa (WEMA) Project of AATF and partners. DH has since gained wide use (Odiyo et al. 2014: 150 -158; Ogugo et al. 2015: 129-139; Wallace et al. 2016: 2365-2378) in Africa. Private breeding programs of private seed companies (which control a significant share of commercial varieties in the maize value chain in African markets) in East Africa are exploring this facility for their hybrid maize development.

Molecular Marker based Applications for Gene discovery, Trait selection and improvement

Conventional plant breeding has generally been based on measurable phenotypic characteristics while molecular breeding explores molecular information at the gene level (short segments of DNA (or "markers") in or near the gene(s)). Markers have been successfully applied to map major genes and quantitative trait loci (QTLs).

Gene discovery — Gene discovery is the process of identifying genes that contribute to the development of a trait or phenotype. Most gene discovery studies utilize DNA-based methods and statistical genetic mapping techniques that use recombination events to determine genetic distance between two loci. This is performed taking the DNA from each individual in the study and identifying the type of marker each has on his chromosomes. Different types of markers, Restriction fragment length polymorphism (RFLP), Amplified fragment length polymorphism (AFLP), Inter simple sequence repeats (ISSR), Simple sequence repeats (SSR), Expressed sequence tags (ESTs), Diversity arrays technology (DArT) and Single nucleotide polymorphism (SNPs) have been commonly used in gene discovery and breeding. However, with the advent of next-generation sequencing (NGS) platforms, several thousands of DNA markers are now being utilized for high-resolution genetic mapping (Dhingani et al 2015: 1072-1079, Bernardo et 2015). These markers are linked to traits of interest and have been used to create linkage maps for QTL mapping. The markers have found wide application in Africa, especially for the mapping of novel genes in several crops in Africa. For example, the CMD dominant gene which is being used for selection against the CMD diseases was discovered in African cassava germplasm. The discovery has resulted in major changes in and the extensive integration of molecular tools in cassava breeding and holds significant advantages in terms of selection in low disease pressure zones. Several African germplasms have also been genotyped and accessed for genetic diversity in the identification of rare/unique alleles (Prasanna 2012: 843-855; Wu et al. 2016: 753-765). Markers have been very useful in the analysis of evolutionary changes driven by mutation including plant-pest co-evolvement over time.

Trait selection and improvement — One of the most dynamic areas of plant biotechnology that has revolutionized agriculture is Marker assisted breeding (MAB). MAB allow segments of DNA that code genes for a specific characteristic to be selected and individually recombined in the new organism. Once the code of the gene that determines the desirable trait is identified, genes that code for unwanted traits can likewise be removed. In a traditional backcrossing program, at least six backcross generations would be needed to recover 99% of genetic background of the recurrent parent. With markers, this could be achieved in under three generations. while the cost of marker-assisted backcrossing (MABC) may be higher than traditional breeding methods in the short term, time savings in cultivar development and release may lead to economic benefits in the long term (Collard et al 2005: 169-196, Morris et al., 2003: 235-247).

The use of markers in breeding has been refined with the use of abundant and more informative markers which have now been integrated in the various MAB approaches leading to better results, increased breeding efficiency and greater genetic gains than would have been possible using phenotyping alone as occurs in classical breeding. MAB approaches have been used for several traits including: the development of abiotic stress tolerance (aluminum and manganese-tolerant crops which can grow in acidic soils, water-inundated soils, salt tolerance, drought tolerance); the development of biotic stress (e.g. bacterial, viral and fungal disease resistance, and insect resistance (Nevame et al 2018:); improving agronomic traits (e.g. yield); generation of higher nutrient levels (e.g. pro-vitamin A, iron, essential amino acids in nutrient-deficient staple crops; delayed over-ripening of fruits and vegetables e.g. to reduce post-harvest losses); resistance to soybean cyst nematode (Young, 1999: 505-510), resistance to cereal diseases (Varshney et al., 2006: 490-499), and drought tolerance in maize (Ribaut and Ragot, 2007: 351-360; Tuberosa et al., 2007: 157-162). The first (Cassava Mosaic Disease) CMD resistant Latin American cassava variety was developed and released in Africa after failure with classical breeding for over 30 years (Okogbenin et al, 2007: 1895-1904; Okogbenin et al 2012: 2576-2586.

With advances in sequencing technologies, more powerful breeding approaches have evolved. An example of such an approach is genomic selection (GS), which is based on the principle that information from many markers can be used to estimate breeding values and search for mutations that underly variation in complex traits. In GS, genomic estimated breeding values (GEBVs) are calculated from the cumulative effect of large numbers of genetic markers covering the whole genome, and these values are used to score new potential breeding candidates. Genomic prediction (GP) combines genome-wide marker data with phenotypic data in a training population to predict the genomic estimated breeding values of untested individuals in a relevant testing population. Genotyping by sequencing (GS) allows the breeder to increase selection intensity, through the use of larger breeding solutions, increased accuracy in selection, increased additive variance due to more robust quantification of genetic variation; and reduction in time interval to obtain individuals carrying the trait (s) of interest. Africa is beginning to integrate molecular markers into breeding programs. However, the pace is slow due to limited skills of breeding teams within the given country.

Previously, many tropical crops grown in Africa suffered from paucity of markers and genomic resources, but in the last 15 years this has been largely addressed through increased investment (Raju et al., 2010: 10-45; Varshney et al., 2010: 452-460; Gautami et al., 2012). Most staple crops in Africa and developing countries now have abundant genomic resources for meaningful genetic studies and most MAB applications (Ribaut et al., 2010: 213-218). The falling prices for genotyping have made outsourcing genotyping services cost effective and accessible to national breeding programs. This has increased more access to genotypic data for African scientists to support breeding activities and to appropriately dissect the genetics of traits for tropical crops. This is a healthy paradigm shift and many NARS in Africa have benefitted from this model with good generation and analysis of molecular data for use in cultivar development. With the increasing molecular power offered by genomics, more genetic information is being unlocked to expedite crop improvement. The coming years are likely to see more use of high throughput platforms for both genotyping and phenotyping applications in Africa (Ribaut et al., 2010: 213-218).

Genetic Engineering (GE) — The inability or challenges of transferring traits across species was a major setback in classical breeding especially in species where genetic variation for a trait of interest is limited. The use of GE allows the transfer of DNA between more distantly-related organisms than would otherwise be possible with traditional breeding techniques. Products developed from this technique are referred to as *transgenic* organisms, or genetically modified organisms (GMO). This technology is faster than other methods for trait introgression if an enabling environment exists. The molecular breeding approach directly manipulates the genome of an organism either by the introduction of one or a few new genes and regulatory elements, or by decreasing the expression of endogenous genes. GE has been useful for simple traits and likewise for multi-gene transfer, through the cotransformation of multiple linked or unlinked genes. Multiple genes are also routinely stacked in transgenic plants by iterative processes involving successive rounds of crossing (breeding stacks) or sequential transformation with cassettes containing different genes to develop transgenic plants (molecular stacks). Nuclear genome transformation is used in most economically important plant species and is also more widely utilized than organelle genome transformation. GE has been successfully used for several traits including protection against insect attack (corn, cotton and potato), tolerance to herbicides in weed control (e.g. corn, cotton, soybean, canola) (Dash *et al.*, 2016:43-57), reduction or removal of toxic components within food such as anti-nutritional factors or protein elements responsible for allergenic responses in foods such as peanuts (Rabjohn et al, 2002: 15-23), and soya (Kleiner, 2002). This technique has utilized anti-sense technology to suppress early ripening in tomatos leading to improvement in quality and flavor. Golden rice was developed through GE to accumulate b-carotene to meet total vitamin A requirements in developing countries with rice-based diets (Ye et al., 2000: 303-305). The use of GE is rapidly growing in Latin America and is projected to be a main driver of agricultural transformation in the continent (Izquierdo and de la Riva 2000). In Africa several GE initiatives are ongoing regarding cassava, maize, rice, banana, cowpea and cotton. Transgenic cotton has been commercialized in Ethiopia, Nigeria, Kenya, Sudan, while transgenic Bt cowpea was recently approved in Nigeria.

Genome editing — As with transgenic technology, genome editing requires a precise knowledge of how the gene works, and the resulting plant must be tested to make sure it functions as intended. This procedure is used to edit genes that were unintentionally mutated during crop domestication, returning them to a more functional state. It is also used to increase or decrease the amount of protein made by a gene. This technology can also be used to change a gene's protein-coding sequence. It is the most precise of all the crop improvement methods. The technique leaves behind no foreign DNA and it is a rapid process. Genome editing can be conducted by site-specific integration, deletion and/or mutation of genes of interest. The latest tools in the genome-editing toolbox are "Clustered Regularly Interspaced Short Palindromic Repeats (CRISPRs)". Among the three types of CRISPR–Cas systems, Cas9 belongs to the best studied type II CRISPR–Cas system. Cas9 is a recent advance in genome-editing technology and is becoming the technique of choice due to its many advantages: it is easy to use, versatile and has the capacity to cleave methylated loci (Hsu et al 2013: 827-832, Lozano-Juste 2014: 284-287). This technique facilitates the direct improvement of less favorable alleles into more favorable alleles. To develop improved crop varieties, it is becoming necessary to utilize genome selection and genome editing collectively. Genome editing shortens the time when back-crossing is conducted between elite varieties and exotic germplasm. CGIAR centers in Africa (e.g. IITA, CIAT, IRRI) are exploring research initiatives on crop improvement based on this technique.

The increasing use of biotechnology tools in breeding programs in Africa has increased crop improvement opportunities for several staple and other economic crops on the continent, including legumes, cocoa, yam, cocoyam, banana, oil palm, pineapple, cotton, tea, coconut palm, plantain, cassava, ginger, cowpea, potato, sweet potato, citrus, sugar cane, finger millet, beans, sorghum, barley, groundnuts, bambara groundnut, tea, maize, guava and ornamentals.

Status and challenges of Crop Improvement Programs in Africa

Crop Improvement is the development or genetic alteration of existing crop varieties, to evolve new varieties with better performance than old varieties. Crop improvement, however, requires access to and use of suitable genetic resources (germplasm), human and physical resources. Over the years different initiatives of national, regional, international and private development agencies have successfully established crop improvement programs in Africa that have resulted in the development of improved crop varieties with desirable traits.

While there has been good momentum with efforts towards crop improvement capacities and the accelerated pace of release of improved varieties in the region, this effort is hampered by insufficient financial resources. Crop improvement research in SSA is carried out mainly within the public sector. Most of the funding received by National Agricultural Institutions (NARIs) is mainly used for paying salaries while only limited funds go to research. Thus, the crop improvement potential of SSA countries is dependent on overall capacity of their respective NARs and the relative allocation of funds. The agricultural research system output has grown greatly in the last three decades, but it has been mainly donor driven.

Africa has a strong human resource base with skills that would benefit agricultural development immensely. However, a significant proportion has been lost to the other continents, especially in the 80s during the implementation of the structural adjustment policies of the International Monetary Fund (IMF) that reduced public investment in agricultural research. This further diminished the human resource capacity of breeding programs that already had too few trained breeders (Guimaraes et al., 2006:1-50). Strong measures have been taken to reposition these programs, but experience is the key to achieving results. The demand for short-term impact by donors is quite a challenge to breeding programs (Ribaut et al., 2008: 21-61) which means that a multi-disciplinary approach must be adopted by African NARS where there is insufficient staff. The number of researchers in Africa, estimated at 198 researchers per million people, is low, compared

with 428 in Chile and over 4,000 in the UK and US. (Kariuki and Kay, 2017).
With limited research funding, only a few crops (mostly staple) receive more attention. Many so called "orphan crops" are under-researched yet critical to providing nutrition for rural populations. Although breeding infrastructure for phenotyping and genotyping platforms is gradually improving, it is still a limiting factor. Some regional labs now exist, for example Biosciences eastern and central Africa (BecA) and IARC labs. However, they are not enough to cover the whole region. There is still low private sector integration in the agricultural research system in Africa. The private sector is a major driver of agricultural development in the developed countries, bringing in investment that is critical for new technologies and the development of crop value chains, along with farmers, consumers, end-users, and other stakeholders. This definitely determines technological priorities and ultimately guides the direction that plant breeding programs take to remain relevant in line with global demand and change.

Crop Improvement Programs in Africa

Crop Improvement is the development or genetic alteration of existing crop varieties, to create new varieties that perform better than older types. However, crop improvement requires access to and use of suitable genetic resources (germplasm), and human and physical resources. Over the years different initiatives of national, regional, international and private development agencies have successfully supported the establishment of functional crop improvement programs in Africa that has resulted in the development of improved crop varieties. These crop improvement efforts have benefited from diverse plant genetic resources (PGR), which is the foundation upon which crop improvement is sustained (Varaprasad and Sivaraj, 2010:1276-1293). PGR are the reservoir of genetic diversity and raw material of important agronomic traits for breeding new plant varieties. Exploitation of appropriate genetic diversity in Africa has resulted in the discovery of new traits and new sources of useful genes for crop adaptation to changing environments, including new pests and diseases. The abundance and robustness of plant genetic resources in Africa is associated largely with its ecological variability and diversity (Nnadozie et al. 2003). The need for continued development of more genetic resources has been further justified by the recent emergence of new pests and diseases in Africa (e.g. MLN and FAW for maize crop) with limited genetic variation in African germplasm to control such biotic stresses. With the climate change threat, there has been a compelling need to explore better genetic resources for improved physiological response and mechanisms to mitigate the effects of new abiotic stress (e.g. increasing drought, flooding, etc.)

Africa Agricultural Technology Foundation's (AATF's) contribution to Crop Improvement in Africa

In the recent past several crop improvement initiatives have been launched in Africa (Table 2) to address the new agricultural challenges on the continent. The synergistic collaborative efforts of the International Agricultural Research Centers (IARCs), Regional Research Centers and National Agricultural Research Systems (NARS) have been key in such initiatives. These efforts have resulted in the development, release and registration of many improved varieties in east and central, southern and west African regions. For example, the Africa Agricultural Technology Foundation (AATF) and partners through the Water Efficient Maize for Africa (WEMA) Project played a key role in the development of hybrid maize varieties/hybrids tolerant/resistant to drought and insects for improved yield (Table 3). Under WEMA, 109 *Climate-smart* Hybrids (Figure 2) comprising 104 conventional DroughtTEGO® hybrids including hybrids tolerant to Maize Lethal Necrosis (MLN) disease were released in five countries. In addition to these hybrids, several inbred lines were also developed by the WEMA Project which have been made available to seed companies through licensing systems to support its efficient delivery in target countries. Breeders in these companies as well as in National Agricultural Research Systems (NARS) outside project countries can access and use these parental lines for further breeding or the release of hybrids in their domain. Three-way hybrids developed in the project have superior yield advantages over the best commercial varieties in the African market by 46–56%. Similarly, inbred lines developed in the project through Doubled Haploids (DH) technology has also shown very impressive performance with 175–213% greater yield than the best available inbred lines. The implication is that seed companies that access these elite inbred lines could have up to three times more seed yield from these new inbred lines per unit area when compared with their current best inbred lines. Under the WEMA project, AATF also developed and deployed five transgenic *Bt* insect-resistant maize hybrids trademarked TELA® in South Africa. In the same project, confined field trials (CFTs) were carried out in Kenya and Uganda for five years to test the efficacy of the *Bt* gene in controlling the spotted stem borer (*Chilo partellus*) and the African stem borer (*Busseola fusca*). Under conditions of artificial infestation by both species of stem borers, maize hybrids containing the *Bt* gene yielded on average, 52% more than the same hybrids (*isogenic*) without the gene. Similarly, preliminary results from the CFTs on stacked drought-tolerant (DoughtGuad® gene) and insect-resistant (*Bt*) traits carried out in Uganda, Mozambique, and Kenya showed that hybrids containing the stacked genes significantly yielded 9 to 98% (Figure 3) more than the *isogenic* hybrids under natural infestation of Fall Armyworm (FAW) and natural or artificial infestation of stem borers. Our results demonstrate that the *Bt* gene conferred partial but significant protection against this new pest – FAW.

AATF and partners have also successfully led the development of a transgenic Bt pod-borer resistant (PBR) cowpea that primarily aims to control *Maruca vitrata*, which is a huge problem in West Africa, causing devastating yield losses if not sprayed. The cowpea was transformed successfully (Higgins et al., 2012: 131-137). Results of the efficacy tests conducted in West Africa showed the Cowpea events, under high *Maruca* infestation pressure (artificial infestation) gave near complete control of *M. vitrata*, 0-6% pod damage for the transgenic events and grain yield per plant increased several folds (Table 4). The agronomic performance of transgenic cowpea has been tested in multi-location trials in Nigeria, Burkina Faso and Ghana. Depending on the pressure of *Maruca*, PBR-Cowpea out yielded the conventional cowpea from between 20% up to more than 100%. Under high pressure of *Maruca* the yield of conventional cowpea is suppressed. So, the higher the pressure of *Maruca* the higher the differences in grain yields. Under CFT farmer managed trials in 2017 almost 2/3 farmers ranked transgenic-Cowpea as their most preferred cowpea. In Farakobah, Burkina Faso, and in Ghana all farmers ranked transgenic PBR-Cowpea as their most preferred cowpea due to its high productivity and earliness. The study conducted in Ghana and Nigeria showed that PBR-Cowpea can be cultivated efficiently with two insecticide sprays to control other pod sucking pest instead the usual 5-10 sprays normally used for the production of cowpea a profitable economic activity.

AATF is also pioneering the development of transgenic rice for nitrogen and water use efficiency including salt tolerance, to address abiotic stresses to improve rice performance under varying production ecologies in lowland and upland conditions. The rice project (NEWEST) has completed proof of concept indicating that positive events have been identified for nitrogen use efficiency with at least one ton yield increase at low, moderate and high nitrogen levels ; and are currently subject to agronomy trials under confined regulatory conditions. In addition to transgenic efforts, AATF has also strengthened breeding initiative for hybrid rice which has led to the development and release of five hybrid varieties including supporting the development of a seed production ICT tool to guide the seed production of parental inbred lines and hybrids. Over 200 hybrids are available for Africa under the Hybrid rice project. Yields of hybrid rice developed are as high as about 10 tons under farmer's condition and with a yield advantage of between 1-5 tons/ha more than the best commercially grown inbred lines in each of the region in Kenya, and Tanzania (Figure 5).

These crop improvement initiatives are offering new innovative products to Africa. In addition to strengthening new products for the markets as part of efforts to transform agriculture along agribusiness paths, AATF has also supported the investments of African breeders and scientists to improve technologies for both conventional and biotech applications for crop improvement, with increased expertise in new fields as well as infrastructural development. For example, insectaries have been built through WEMA to support insect resistance screening (phenotyping) for selection of best hybrids to aid entries for advanced evaluations at national performance trials (NPTs) and also for baseline susceptibility studies to develop insect resistant management (IRM) strategies.

Creating enabling environment and sustainability systems for uptake, diffusion, and upscale of newly developed varieties

Policies and Regulation — There is a need to create and operationalize policies and regulations to guarantee that products developed through advances in biotechnology are taken up and used for the benefit of targeted end-users (farmers, consumers, industries etc.). Policies to support input supply, private sector investment, infrastructural development (storage, roads development, seed systems, credit systems, increased agricultural funding etc.) are crucial to stimulating the contribution of new varieties to agricultural growth and the economic development of SSA countries. The implementation of sound policies to support agricultural development is still a major concern in Africa. For example, in 2003, at Maputo, Mozambique, African heads of state made a commitment to devote 10% of their national budgets to agriculture; 15 years after the decision, only 20 countries are well on track while 27 countries are not. The regulatory terrain for GM crops in Africa is a labyrinth of evolving policies, laws and regulations that requires adept capacity to navigate through them. Different countries have their specific regulations governing trials with diverse elements that could complicate and hinder the cross-border transfer of technologies. Support of key decision makers, influencers and allied constituencies are all vital to marshalling the necessary political goodwill needed to obtain the product release for some technologies (GMO). While biotech crops have received some positive reception in the past two decades, a polarized debate pitting proponents of GM technology on the one hand and opponents of these crops (who advance misinformation and fears) on the other, has made this a subject of intense public policy discourse. This dichotomy of positions has only served to create confusion among decision makers as it affects the progress of deregulating GM crops in the continent. An enabling environment for appropriate regulatory frameworks and policies is required to avert narrowing the scope of scientific and technological endeavors that could seriously constrain options for agricultural solutions (Richards 2005: 199-214). In line with its mission, AATF has made significant progress in terms of supporting the development of science-based risk assessments within various regulatory systems and policies in Africa. It has played critical roles in many countries for innovative biotechnology projects (especially transgenic technologies that are still new in Africa), including facilitating the implementation of product development of these projects. In the last 10 years, AATF working with partner institutions has secured some 60 permit approvals in nine countries for testing transgenic crops such as *Bt* maize, *Bt* cowpea, GM rice and GM banana. While assembling and submitting a solid application is necessary, inadequacies and gaps in regulatory systems in Africa can seriously hamper bids to secure a positive decision for the general release of GM products. Relevant adequate regulatory systems are expected to provide suitable business environments that remove risk and allow new product development, testing and commercialization (Dethier & Effenberger, 2012: 175-205). AATF has learned that the ultimate decision on general release of transgenic crops, although primarily dependent on product safety information and the existence of governing legislation - is usually a weighty matter subject to political overtones. The aspirations of AATF to deliver innovative technologies to African farmers will only be realized with the emergence of a conducive policy and regulatory environments that promote the adoption of GM crops in Africa, a huge task (but accomplishable) given the varying regulatory status of GM technology in African countries (Figure 6).

Capacity building — Once enabling technologies in biotechnology and genomics become available, financial resources often dictate the degree to which these innovations are integrated into existing plant breeding programs. The costs associated with the development, establishment, and operation of molecular plant breeding are greater than conventional plant breeding practices (Koebner and Summers, 2003: 59-63; Morris et al., 2003: 235-247), requiring significant investments in new research infrastructure and intellectual capacity. Such resources are a major hindrance in the public sector of R&D in Africa due to funding challenges. In addition to the valid scientific and economic concerns that have either delayed or prevented the full scale adoption of molecular techniques in plant breeding, there are other major concerns. Given the rapid evolution of modern breeding especially for those involving molecular techniques, regular training and refresher courses are needed for expertise updates in the application/ utilization of plant breeding for practicing breeders to take full advantage of the new developments in the field. There is currently a growing recognition that increased investment in plant breeding capacity and translational research linking molecular methods with breeding objectives is necessary to fully realize the potential of recent advances in biotechnology and genomics (Guimara˜es and Kueneman, 2006: 1-50; National Research Council, 2008).While poor infrastructure and lack of trained personnel have previously limited the adoption of MB, the falling prices for genotyping have made it more affordable . Unlike genotyping, field phenotyping cannot be easily outsourced. Development and maintenance of research phenotyping infrastructures (e.g. cameras, sensors, computers and highly modified devices for the collection of very precise phenotypic data) are crucial to the sustainable delivery of improved consumer products that can be adopted.

In a bid to strengthen plant breeding capacity in the continent, a number of sound financial outlays have been supported by investors. The Alliance for a Green Revolution in Africa (AGRA) has, over the last 12 years, invested over US$4m to train plant breeders for the East and Southern Africa region through the Improved Masters in Cultivar Development for Africa (IMCDA) program implemented in partnership with the Africa Center for Crop Improvement (ACCI), funded by the Bill and Melinda Gates Foundation. A similar set up was created for West Africa (West Africa Center for Crop Improvement – WACCI). The African Plant Breeding Academy also played critical role in the training of African plant breeders in the most advanced theory and technologies for plant breeding. The plant breeding capacity situation has improved somewhat on the continent through the activities of these programs. Crop development processes now require a multidisciplinary approach to enhance efficiency and speed, training is needed to build a multi-disciplinary crop improvement team to conduct modern integrated breeding to address food security challenges on the continent.

Commercial agriculture and expanded markets — Beyond the need to improve food and nutrition security, there is a need to rapidly develop the African economy and improve the livelihoods of farmers and others in the agricultural value chain. While biotechnology has improved the potential to increase crop productivity, the sustainability of high production will largely depend on structured and organized markets to absorb the excess produce of farm households from the use of improved varieties. This is expected to result in more income which will permit such farmers to have strong purchasing power in order to acquire the best technologies and apply best modern practices to achieve efficient production. This is critical to driving the transformation of farmers from subsistence to commercial agriculture. The power of biotechnology is rapidly driving high value-added products and there is high priority for developing market systems to support the new breeding paradigm. Strengthening farmer access to regional and international markets are thus crucial. Breeding to enhance food-safety and quality attributes must improve so as to facilitate greater access of African produce to international markets. Biotechnology provides and offers much promise in this area for agribusiness. Measures must therefore be taken to ensure a strong bias for breeding and biotechnology research towards commercial markets. Innovative market driven products will attract a lot of investment from the private sector which will allow for sustainable business operations (Pray, Gisselquist & Nagarajan, 2011). The WEMA case study of AATF provides a very good example of private sector investment. The private seed companies are partnering with AATF through commercialized seed production to facilitate access to certified seeds of high yielding drought tolerant hybrid maize. Farmers in turn have seen their yield and income transformed through cultivation of these hybrids.

Stewardship — Seed-based technologies have been facilitated principally by breeding and biotechnology tools. Therefore, seed, as a biological product is the most effective, cost-efficient and at the same time limiting factor in the effective delivery of technologies at low cost to small holder farmers in Africa. Past experiences indicate that a large portion of conventional seeds of crop varieties/hybrids developed through classical breeding never make it to the ultimate end-users (farmers) or if they do soon lose their genetic purity overtime in a few years due to poor stewardship and seed systems. This can occur by repeated use of farm-saved seeds by a majority of SHF farmers or poor isolation, poor detasseling in case maize, poor storage, etc. with an attendant decline in quality resulting in poor productivity. Thus, a Stewardship guide/strategy and education and training support to farmers, as part of the development of Africa's seed systems and value chain in Africa, are integral to the process of building sustainable agriculture for the continent including maximizing returns on investment in plant breeding and biotechnology. Stewardship activities span from product development through to deployment and commercialization to ensure that products comply with policies, regulatory demands and quality management systems (QMS) requirements of both national (countries) and international set standards. It is therefore critical to put functional audit systems in place as part of QMS as outlined in quality assurance/quality control (QA/QC) mechanisms. Stewardship functions are much more critical for transgenic crops where seeds are regularly monitored for traits of interest (e.g. transgenes) to ensure seeds that are delivered in the input markets are in line with farmers´ expectation for the results they desire. Biotechnology tools in the form of molecular markers or gene stick allow us to assess the genetic integrity (trait purity) of products developed from crop improvement pipelines. Through stewardship functions, seed companies effectively comply with seed production principles, as well as meeting best storage conditions prior to market entry. Stewardship functions therefore helps to ensure that technologies are used in a responsible a bid to support long-term durability of the very technologies for the benefit of farmers in addition to averting the loss of expensively assembled technologies. For example, the improper use of Bt crops in South America has seen the development of resistance to pests in some Bt strains. AATF has developed an IRM plan to support the use of Bt maize and cowpea in aid of the proper use of these technologies.

Conclusion

The improvement of varieties developed in the 20th century was achieved through improved knowledge of genetics. However, the challenge of feeding the ever-increasing African population in the face of emerging challenges such as climate change, emerging pests and diseases, and the need for new market niches, has resulted in increasing exigency to explore recent advances in plant breeding and plant biotechnology. Crop improvement advances must be supplemented by a battery of decision support systems: regulatory, seed supply chain, technology and product stewardship, advocacy and outreach, amongst others, to develop new varieties with the capacity to achieve high yields. The systems ought to be built on strong partnerships of players involving both public and private sectors of crop value chains critical to sustainability. For sustainable impact, breeding technologies selected for improved food and nutrition security, must guarantee scalability and replication of results as well as ensure effective delivery to farmer, and support value chain development in Africa.

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Techniques	**Applications**
Tissue culture/ cryopreservation	Conservation and management
Embryo rescue	Interspecific crosses
In vitro (e.g semi autotrophic hydroponic)	Rapid ramping of seeds (clonally propagated materials
MABC	Fast track transfer of traits to elite lines
MABC	Exploring useful traits from the wild species
MARS, genomic selection	To efficiently combine best alleles
DH	Rapidly develop parental lines (e.g inbred lines)
Heterotic groups	Assigning accessions and parental lines into heterotic groups
Genotyping	Clustering to identify genetic relatedness or not
Genome editing, GE (transgenics)	Transferring traits across species

Table 1: Biotechnology techniques in crop improvement

Project	**Product/Genes**	**Trait**
WEMA	• *Bt* • CSPs	• Stem Borer resistance • Drought tolerance
Striga, Cowpea, Banana, Casava, Potato	• Imazypayr Resistance gene • *Cry1Ab* • *Hrap, Pflp* genes • *Hrap, Pflp* genes • *Pflp, EFR* genes	• Herbicide resistance • *Maruca vitrata* resistance • Bacterial Wilt resistance • Bacterial Blight resistance
NEWEST Rice	• HvAlaAT • AtuIPT • OsNHX1	• Nitrogen Use Efficient (NUE) • Water Use Efficient (WUE) • Salt Tolerance (ST)
Hybrid Rice	• Parental lines (S and P)	• High yields • Quality • Aroma • Milling value

Table 2: AATF projects and Accessed Technologies

Breeding Pipeline	**Hybrids**	**Parental lines**
CIMMYT	5299	9794
MONSANTO	5219	3784
KENYA	425	507
MOZAMBIQUE	-	709
SOUTH AFRICA	296	4310

Table 3: WEMA breeding pipelines in 2014: Hybrids & Parental lines

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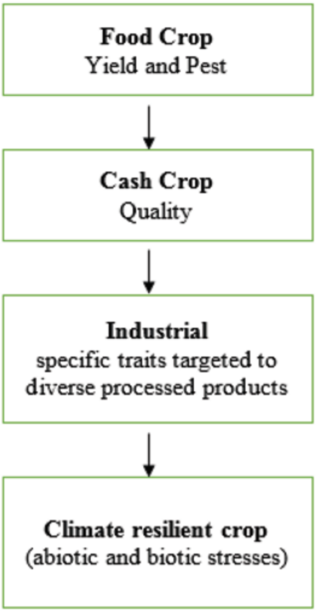

Figure 1: Generations of trait development in crop breeding in Africa

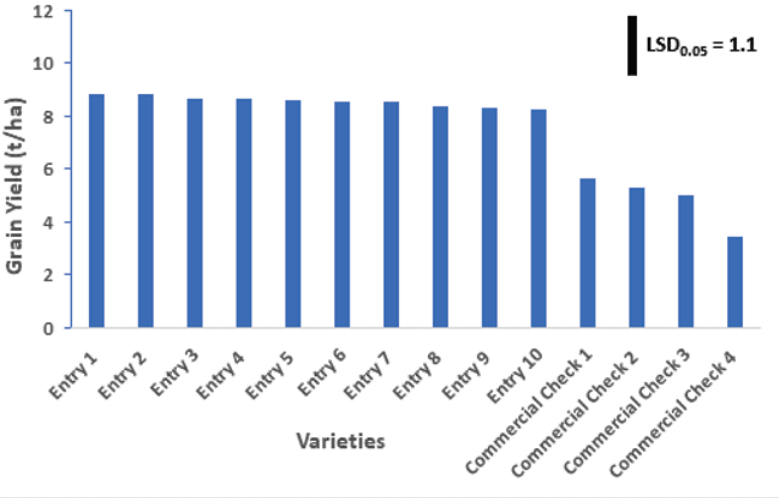

Figure 2: Performance of elite three-way hybrids by crossing elite drought-tolerant DH inbred lines × elite drought-tolerant DH inbred lines

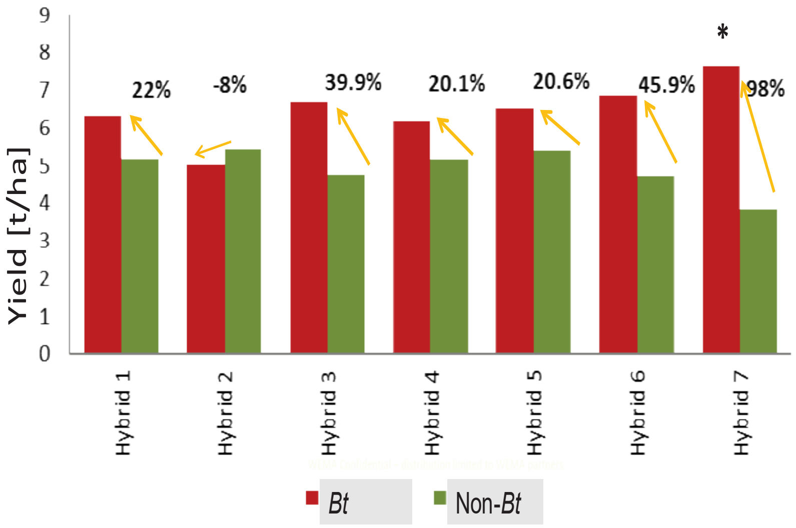

Figure 3: Performance of stacked drought-tolerant and insect-resistant traited hybrids (Bt; Red bars) and isogenic hybrids (Non-Bt; Green bars) under natural infestation of stem borer and FAW in Mozambique, 2017

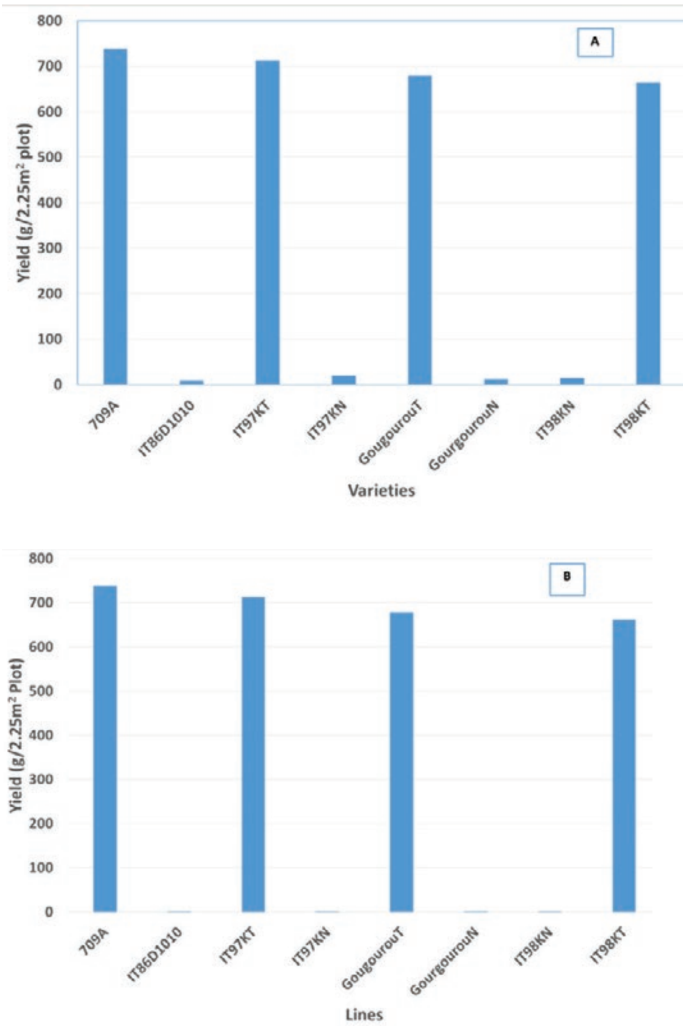

Figure 4: Average yields of four PBR-Cowpea lines and their conventional isogenic lines in the efficacy test of the Cry1 Ab gene (names ending with T means transformed with Cry 1Ab Bt-gene, line 709A is also a PBR-cowpea); A=Total grain yield; B=Healthy seed yield; plants were infested with larvae of Maruca vitrata raised in a lab on artificial diet; each mean is computed from four replications; CFT, Farakoba, Burkina Faso, 2016 (Source: INERA)

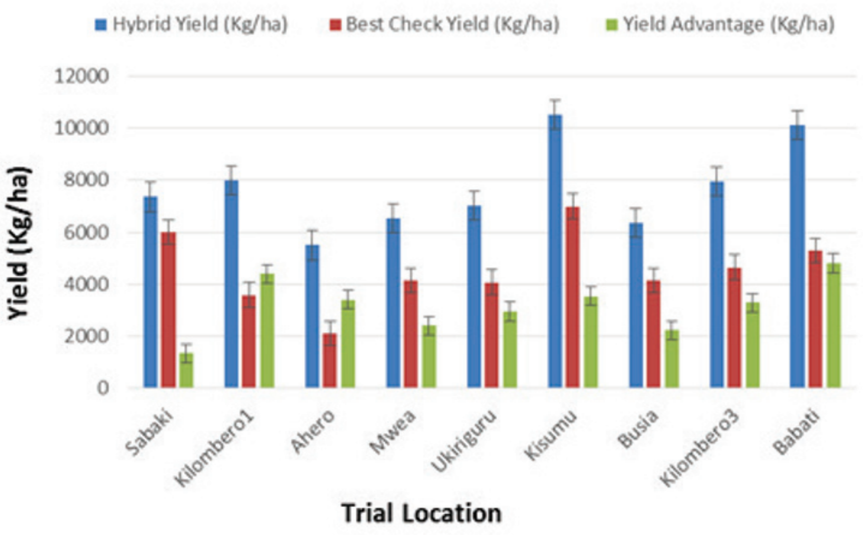

Figure 5: Results of the best performing hybrid in each of the 9 irrigated locations in project counties

Countries with GM Project Activities

1. South Africa
2. Burkina Faso
3. Nigeria
4. Cameroun
5. Ghana
6. Ethiopia
7. Kenya
8. Tanzania
9. Mozambique
10. Malawi
11. Sudan
12. Egypt
13. Swaziland

Notes on colour schemes

1. **White**: denotes countries with no regulatory systems
2. **Yellow**: denotes regulatory systems that are work-in-progress
3. **Red**: denotes regulatory systems that are prohitive to GMOs
4. **Lime**: denotes interim, partially developed systems that aonly permit CFTs
5. **Green**: denotes fully developed and functional regulatory systems

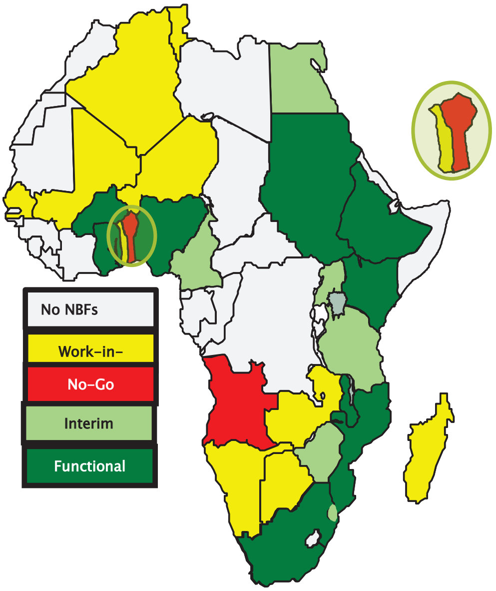

Figure 6: Status of regulatory terrain for GM crops in Africa