The Role of Plant Breeding in Enhancing Climate Resilient Agriculture Practices

DR. M. N. ISHAQ
(*Plant Breeder/Director*)
National Cereals Research Institute, Badeggi, Niger State, Nigeria

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INTRODUCTION

Plant breeding has always played a pivotal role in human history, revolutionizing agriculture to feed the ever-growing population.

Climate resilience in crop production is the ability of a plant/crop to survive and recover from the effects of climate change through important agricultural practices which may include:

1. Soil organic carbon build-up or carbon sequestration
2. In-situ moisture conservation
3. Residue incorporation instead of burning
4. Water harvesting and recycling for supplemental irrigation
5. Growing biotic and abiotic resistance/tolerant varieties

Why Climate Resilient Agriculture?

Understanding the Problem at Hand -- The Climate Change

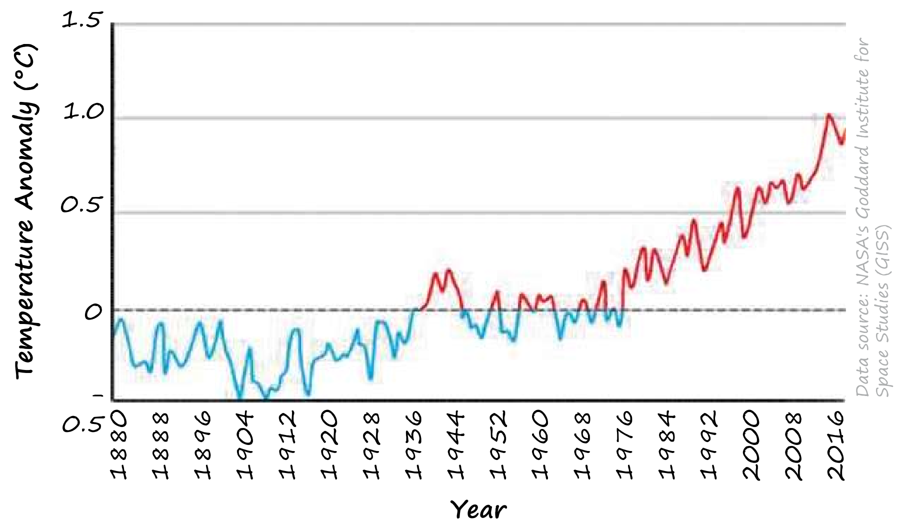
- *Not about who or which region is responsible*
- *Not about the climate justice*
- *Not about the social justice*

But

As a threat to us and our future

Climate change is one of the defining issues of our time, receiving huge attentions from various scientific communities around the word

Weather, Climate, Natural Climate Variability and Climate Change: *What make the difference?*



The planet is becoming warmer; the climate is changing.

Scientists use statistical tests to determine the probability that changes in the climate are within the range of natural variability

Weather is the temperature, humidity, precipitation, cloudiness and wind that we experience in the atmosphere at a given time in a specific location

Climate is the average weather over a long time period (30 – 50 years) in a region

Natural climate variability refers to natural variation in climate that occurs over months to decades. That is changes temperature, rain and wind patterns in many regions over about 2 – 7 years.

Climate change is a systematic change in the average temperature and cycles of weather over a long period of time (decades or longer).

The Facts about the Climate Change: *Accepting the need for climate resilient agriculture*

- Climate change is happening now
- It is being driven primarily by human activities
- It is already affecting developing nations
- It will affect all sectors and countries
- We can do something to reduce its impacts and progression

Climate is always changing: ***Why is climate change of concern now?***

All major climate changes, including natural ones, are disruptive. Past climate changes led to extinction of many species, population migrations, and pronounced changes in the land surface and ocean circulation.

The speed of the current climate change is faster than most of the past events, making it more difficult for human societies and the natural world to adapt.

Recent estimates of the increase in global average temperature since the end of the last ice age are 4 to 5 °C (7 to 9 °F). That change occurred over a period of about 7,000 years, starting 18,000 years ago.

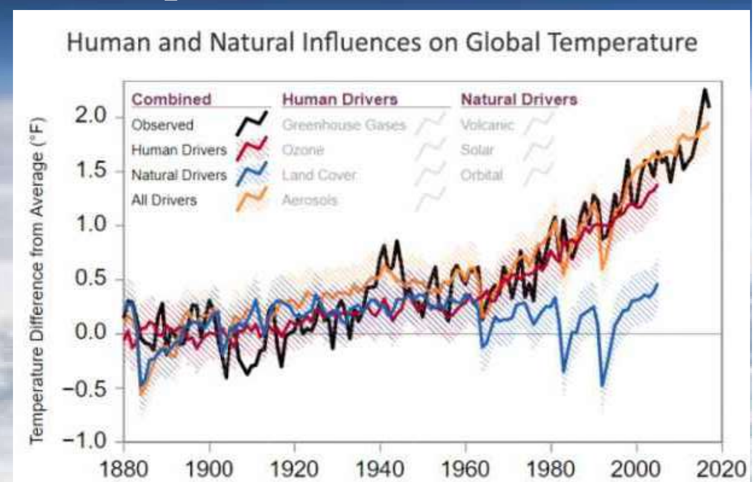
This speed of changing is more than ten times that at the end of an ice age, the fastest known natural sustained change on a global scale.

The Basis of the Climate Change

At its most basic, climate change is caused by a change in the earth's energy balance — how much of the energy from the sun that enters the earth (and its atmosphere) is released back into space.

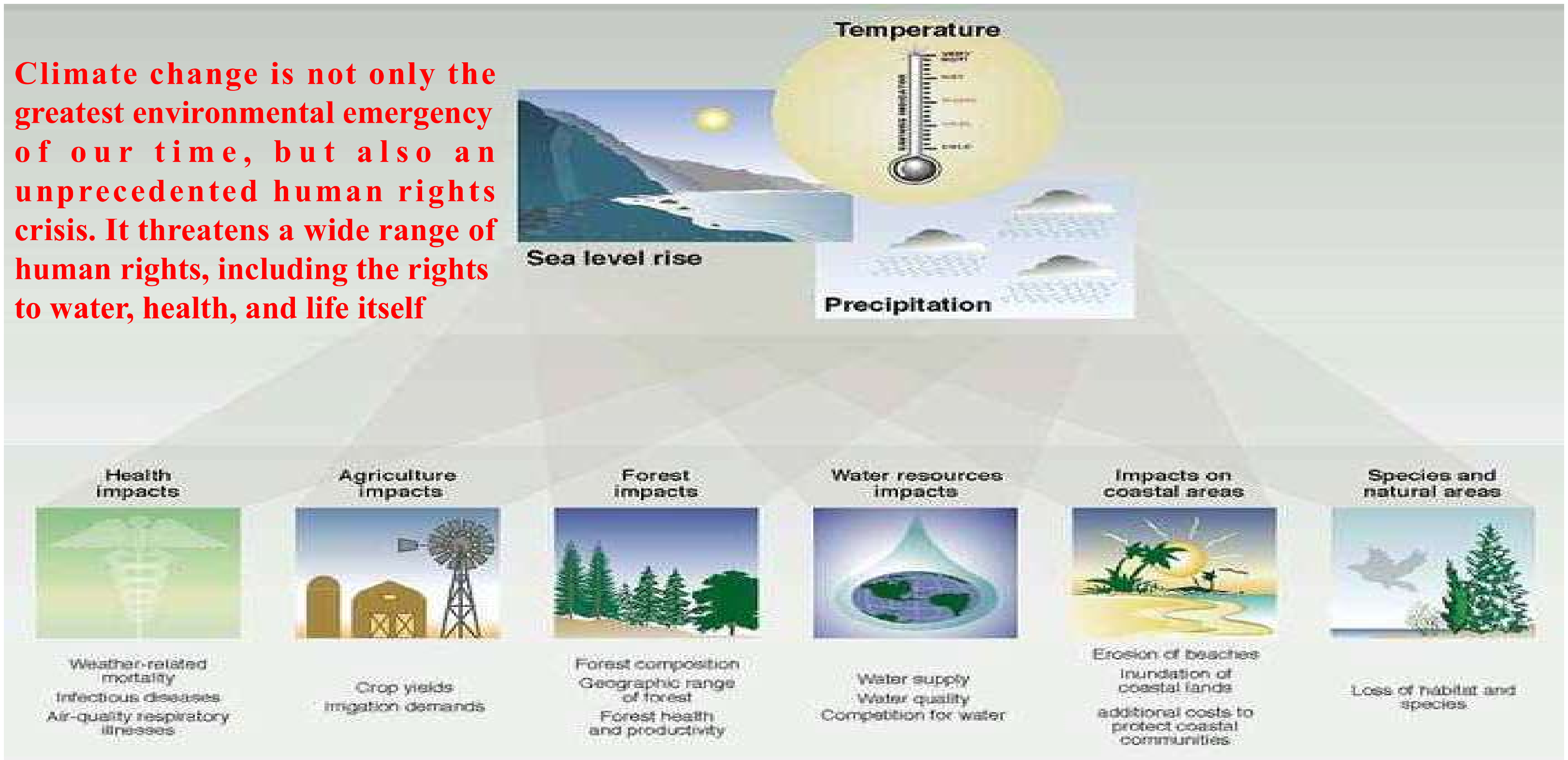
The disturbance to this balance of incoming and outgoing energy is cause by:

- Natural processes
  - Volcanoes
  - Tectonic plate movement
  - Changes in the sun
  - Shifts in Earth's orbit
- Human activities – any activity that releases "greenhouse gases" into the atmosphere



The greenhouse gases in the atmosphere, including water vapour, carbon dioxide, methane, and nitrous oxide, act as heat trap: keeping Earth's surface and lower atmosphere more warm than ever

Climate Change Impacts: *The change will affect all sectors and countries*



How much climate change? How much Impact?

Rise in ^{0}C	Impacts
1-2 ^{0}C Above pre-industrial	Major impacts on ecosystems and species; wide ranging impacts on society, including developing county agriculture.
1.5 – 3 ^{0}C	Greenland ice-cap starts to melt irreversibly (7 m)
2 - 3 ^{0}C	Major loss of coral reef ecosystem; considerable species loss; large impacts on agriculture; water resources; health; economies.
	General increase in droughts and extreme rainfalls as the temperature increases. Up to 88cm sea level rise in next 100 years.
2 - 3 ^{0}C	Terrestrial carbon sink becomes a source.
1 - 4 ^{0}C	North Atlantic circulation collapses
2 - 4.5 ^{0}C	West Antarctic ice sheet collapses (5 m)

Source: David, 2006

The Climate Change in Nigeria: *Unprecedented drought and floods are evident in Nigeria*

Nigeria is particularly vulnerable to the impact of climate change in many fronts considering its geography, climate, vegetation, soils, economic structure, population and settlement, energy demands and agricultural activities (Adebimpe, 2011).

The increase in drought, scarcity of food instigated somewhat by irregularities in rainfall, over flooding, to mention but a few, are all evidence of the impact of climate change in the country

The biggest threat remains the growing climate unpredictability, which makes subsistence farming difficult

Our crop varieties are failing due to changing in the normal

Declining rainfall in desert-prone areas in northern Nigeria is already causing increasing desertification

The food basket in central Nigeria is becoming empty

The coastal areas where fishing is the source of livelihoods is being destroyed by the rising waters

The Good News: ***There is a lot we can do about the climate change***

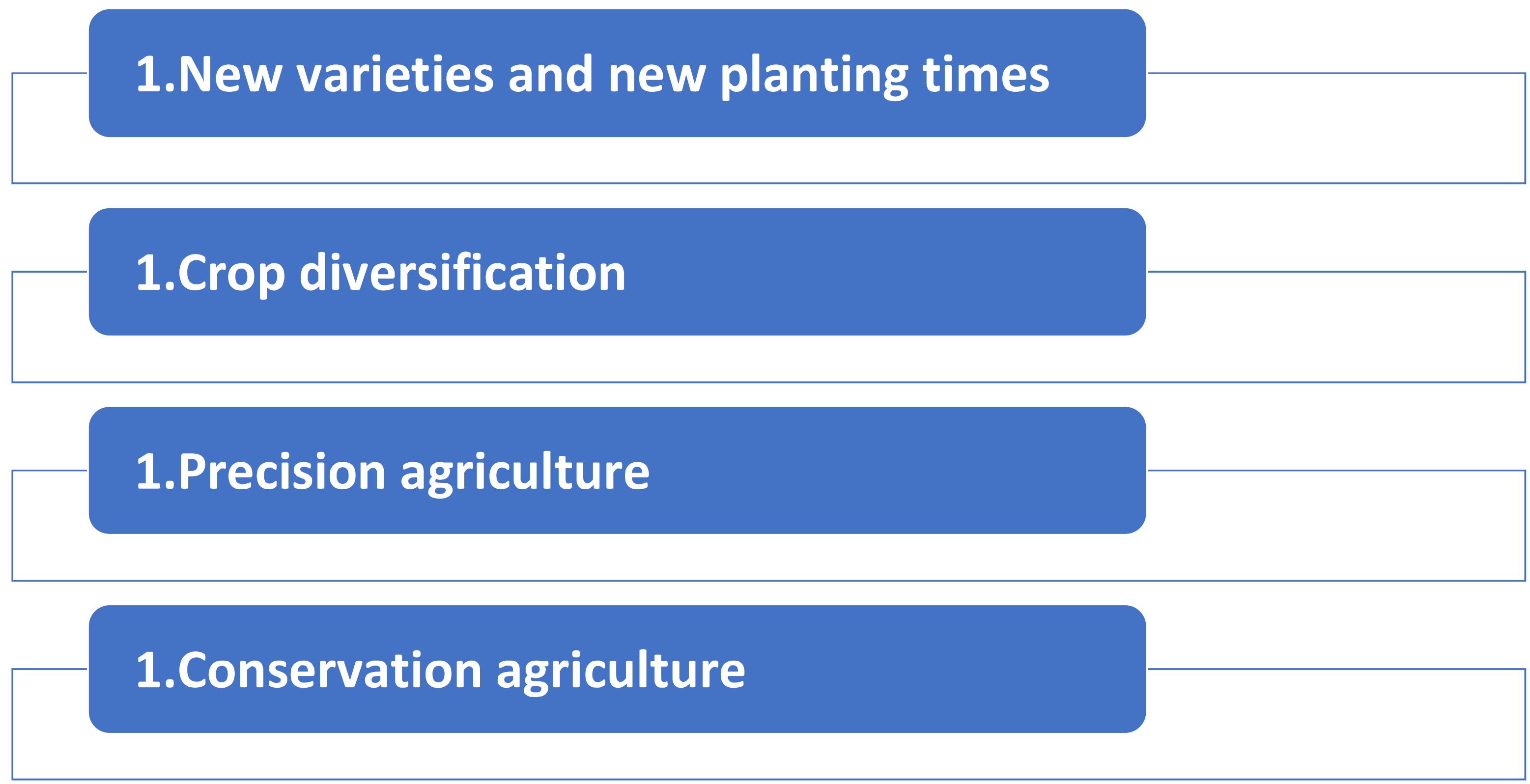
In general, climate solutions fall into three big buckets — “mitigation”, “adaptation” and “Resilience”**.** *However, these concepts are not distinct, and are all inter-related*.

Mitigation refers to “measures to reduce the amount and speed of future climate change by reducing emissions of heat-trapping gases or removing carbon dioxide from the atmosphere

Adaptation refers to measures taken to reduce the harmful impacts of climate change or take advantage of any beneficial opportunities through “adjustments in natural or human systems

Resilience means the “capability to anticipate, prepare for, respond to, and recover from significant threats with minimum damage to social well-being, the economy, and the environment

Climate Change Adaptation Options for Crop Production: ***The Plan for New Normal***



Technological Approaches towards Climate Resilient Agriculture

Some important practices that assist to adapt the climate changes for crop production including:

(i) Building resilience in soil: Tillage management, avoid bare soil, fertilizer application after mandatory soil testing, increase soil carbon through organic manure, green manuring, crop rotation or intercropping with legume sequester carbon and biochar

(ii) Adapted cultivars and cropping systems: Crop diversification, shallow-deep root and legume-cereal cropping system, improved early/short duration cultivars for tolerant against drought, heat and submergence capturing optimum yields despite climatic stresses

(iii) **Rainwater harvesting and recycling**: Inter-row water harvesting, inter-plot water harvesting, in farm ponds and reservoirs and recycling

(iv) **Farm machinery**: Chisel and para plow to opening the furrows which conserves rain water, laser leveler helps in increasing nutrient as well as water use efficiency

(v) Crop contingency plans: Livestock and fishery interventions

(vi) **Weather based agro-advisories**; Automatic weather stations establishment at experimental farms and mini-weather observatories records for real time weather parameters such as rainfall, temperature and wind speed, which customized through agro advisories and improve weather literacy among the farmers

Climate Resilient Plant Breeding: *Adapting to the New Normal*

The basic role of plant breeding is to address the crop productivity problems through genetic manipulation; providing crop variety options to farmers.

This role is an ever-important topic, not the less in the face of the climate change which causes various abiotic stresses such as heat stress, drought, waterlogging, and cold stress, affecting yield and quality of agricultural crops.

Plant stresses trigger different and significant changes in plant gene expression, metabolism, and phenome, and therefore the research on crop adaptation to stressful growing conditions is of great interest.

The normal condition for agricultural prediction is now shifting to new normal, requiring new ideals and inputs. A perfect regional crop is being affected by the climate change and dramatic unpredictable weather, translating to crop options and practices for farmers.

Rescuing the humankind from imminent threats to agriculture posed by weather fluctuations, rapidly evolving pests and limiting resources; climate-resilient crop breeding is inevitable.

Climate Resilient Plant Breeding: *Adapting to the New Normal* ***Cont'd***

Climate-resilient crop breeding is an economical, feasible, and environmentally friendly method of adaptation to abiotic stress, but due to the complexity of the plant traits, it requires unused research approaches.

Traditional plant breeding systems have contributed to massive and rapid yield increases in many crops, as well as increased tolerance to a variety of biotic and abiotic stress

However, longer time invested in variety development and breeding cycles presents a stumbling block to an accelerated response of plant breeders to the growing demand for food production

The challenge that most plant breeding systems face in the 21st century is to increase crop productivity by speeding up the breeding of climate-resilient crops; Even equipped with improved knowledge of gene function and the development of technologies like gene editing, plant breeders still face challenges due to narrowed genetic bases and uncertain climate across the globe

It is anticipated that the integration of multi-disciplines and technologies into three schemes of genotyping, phenotyping, and enviro-typing will result in the delivery of climate change-ready crops in less time.

Recent advancements in genomics, high throughput phenomics, sequencing and breeding methodologies along with state-of-the-art genome-editing tools in integration with artificial intelligence open up new doors

Roles of plant breeding in climate resilient agriculture: ***Developing new skills in multi-genotypic breeding***

The Intergovernmental Panel on Climate Change (IPCC) established that climate change would reduce yields per hectare of wheat, rice, and maize by considerable percent per decade starting from 2030: Calling for all hands on deck for the climate resilient agriculture.

Adapting crops to climate changes has become an urgent challenge which requires some knowledge on how crops respond to the climate related stresses, including drought and temperature stress; pests and disease, salinity and waterlogging.

In the context of climate resilient agriculture, plant breeding must address more diverse needs which are capable of enhancing crops' adaptive capacity in its broadest sense. In this case, both the crop evolutionary changes and plastic ecological responses must be focused holistically.

Developing new skills in multi-genotypic breeding, focusing on expansion of the biological bases that agronomists and farmers rely upon, is the utmost role of the plant breeding now than ever. The so-called "genetic gain" must not only consider the benefits reaped by a farmer using an improved variety at the level of his/her plot, but also its expected economic, social and environmental impacts on a larger scale in the event of a wider dissemination of this variety.

Knowledge and adoption of *New Breeding Approaches,* capable of sufficient breeding progress, should be encouraged in every plant breeding system.

Adequate understanding of how to exploit the crop wild relative for the desired genes and the use of biotechnology will enhance the plant breeding contributions in this climate change era.

Exploring Untapped Hub of Genetic Diversity: Crop wild relatives (CWR)

To make crop adaptation feasible in the era of changing climate, there is indispensable need to breed the crop plants with diverse genetic background: using crop wild relatives with broader adaptation to environment and climate related stresses.

There is need for active and focus pre-breeding activities capable of establishing effective linking of desirable traits of CWR to the modern cultivar development by providing breeders with wild genetic diversity in a more immediately usable form.

The genetic potential of wild relatives (primary, secondary and tertiary gene pools) has exploited successfully in different crops like rice, wheat, maize, etc to generate elite breeding lines/cultivars/genotypes, to overcome the linkage drag.

The crop wild relatives (CWRs) are good reservoir of untapped genetic diversity that can be used to improve the numerous trait of interest including resistance/tolerance against diseases, insect pests, drought, salinity, cold, heat and good agronomic adaption with quality improvement.

Development of desirable genotypes through effective transition of desirable genes from CWR

Genetic Resources	Germplasm screening	Pre-breeding activities	Breeding Program
Crop Wild Relatives Wild species/landraces Gene bank Gene pool	Evaluation of wild relatives or germplasm accessions Identifying promising donors via high throughput screening	Interspecific hybridizations Development of large population Precise phenotyping and genotyping Identification of promising introgression lines Genome-wide association study (GWAS) Haplotype breeding	Working collection from pre-breeding populations Variability enhancement in the working collection Markers assisted selection (MAS) Genomic selection Superior genotype testing under multi-environmental testing for desirable traits Desirable genotype crossing with local varieties or adopted as a new variety

Exotic introgression into elite varieties - *CWR Cont'd*

Interspecific or intergeneric hybridization of wild species are used mainly for the introgression of disease and insect resistance into crops although drought, cold, heat and salinity tolerance have also been addressed in some staple crops

Another potential technique to enhance genetic diversity and facilitate crop vigour with adaptation to different environmental niches is creating the polyploidy crops mimicking natural evolution through hybridization

Enriched genes for biotic and abiotic stress resistance of CWR can be studied using comparative pool sequencing of genome assemblies, elucidating the potential genomic segments responsible for adaptation to different ecological niches. These have been explored in wild relatives of many crops including chickpea, barley and maize

To address the diversity within species, pan-genomics based on entire gene repository of a species can reveal the genetic variations such as structure variants (SVs) and single nucleotide polymorphism (SNPs) abundantly found in plants

Larger pan-genomes including both wild relatives and cultivars can acquire glut of dispensable genes resulting in phenotypic variations; thereby easing out with characterization of the trait associated genomic variants

To tackle the deadly rust diseases in wheat in the context of changing climate, several pan-genomic R genes have been successfully identified and cloned from wild diploid wheat *Aegilops tauschii*

De novo domestication for future crops - *CWR Cont'd*

Most staple crops are grown majorly in the regions other than where they were originally domesticated

The wild relatives and landraces of most stable crops exhibit better adaptation to local climate in their native regions.

Therefore considering the risks of introducing foreign alleles into cultivars, other potential technique for developing climate-friendly crops is de novo domestication

In the scenario of climatic change, there is chance to leverage this opportunity to use those underutilized or orphan crops

A pipeline strategy has been proposed for domestication of wild germplasm in some orphan crops such as quinoa

In addition to direct planting of non domesticated crop plants, relatively advance methodology of CRISPR/Cas9 boosts the wild germplasm domestication by editing of domesticated genes. For instance, editing in wild tomatoes (*Solanum pimpinellifolium*) and ground cherry (*Physalis pruinosa*) mainly focused on flower improvement, plant architecture improvement, fruit size, fruit number and nutritional content

It is evident from such a few successful introgressions of domesticated genes that use of wild germplasm in regular plant breeding is quite promising in countering the effects of climate change on agriculture

Introgressiomics approach for adaptation to climate change - *CWR Cont'd*

The actual potential of the CWR in plant breeding largely remains under exploited due to linkage drag and frequent breeding barriers with the crops

Introgressiomics approach allows mass scale development of plant material and populations with introgression lines from CWR into the genetic background of crops

This pre-emptive breeding technique could be focused or unfocused depending upon the objective

Besides genetic analysis of traits present in CWR, MAS driven generation of chromosome substitution lines (CSL), introgression lines (IL) or MAGIC populations allow the development of genetically characterized elite material

Genomic tools like high throughput molecular markers facilitate the characterization and development of Introgressiomics populations, which can be easily incorporated into major breeding programs for coping with the accelerating environmental challenges

Some other techniques for CWR use - *CWR Cont'd*

After the introgression into domesticated background from CWR, populations such as backcross populations (BC), recombinant inbred lines (RILs), doubled haploids (DH), near isogenic lines (NILs), multiparent advance generation intercross (MAGIC) populations as well as nested association mapping (NAM) populations are developed to study the introgressed gene(s)

After mapping the desirable genes on to the genome and their genotypic validation with molecular markers, they are further deployed using Marker assisted selection (MAS). Systematic screening of the huge number of progenies with MAS enhances the efficiency of breeding program.

Genomic scans reveal candidate domestication and improvement loci as well as post-domestication introgression using CWR to be further harnessed in the scenario of climatic challenges. In case of CWR, high throughput sequencing offers a cheap and rapid way to deploy thousands to millions of markers for mapping purposes

Reduced representation techniques as genotyping by sequencing (GBS) or even nimble exom capture have been exploited to this effect in several CWR species already. These technologies offer rapid marker density as required for rapid fine mapping and can saturate mapping populations in terms of capturing all of the recombinants

The availability of a reference genome sequence in CWR during recent times greatly boosts the use of high-throughput sequence data. Some large scale genomic sequencing and re-sequencing programs are well underway often with reduced representation methods.

Potentially revolutionary technology in modern plant breeding like genome editing has enabled scientists to alter genome of any organism with unprecedented precision without involvement of any foreign DNA. These approaches will allow the use of this information from more distantly related, cross-incompatible CWR and domesticated species to be further utilized in crop improvement

Biotechnology: *An indispensable breeding toolkit for climate resilient agriculture*

Considering the various direct and indirect impacts of climate change on food production and agriculture, the sophisticated techniques laden biotechnology toolkit remain the big hope in addressing the challenges of developing the stress tolerant food crop cultivars in this hour of need.

Adequate knowledge and adoption of recent advances in biotechnology tools is very critical. Roles of all stakeholders must be optimal; while the governments and others have the responsibilities of ensuring the availabilities of the required tools, breeders and others must show readiness to learn and exploit the technology.

Recent advances in biotechnology tools have the potential to understand the function of genes/QTLs that govern the economic traits, and applying this information's to Climate-Smart Plant Breeding.

For plant breeding roles to be optimized, emphasis must be on collaborations and interactions on the recent advancements in agribiotech to get acquitted with the technologies and put them to use.

It is really the high time to shift resilience from conventional breeding to genomics-assisted crop improvement techniques in order to achieve more sustainable and efficient agriculture.

The importance of appraising and reappraising of the recent and important plant breeding technologies in addressing issues around climate resilient agriculture can not be overemphasised.

Biotechnology Cont'd

Marker assisted breeding (MAS): The ultimate goal of plant breeding (assembling multiple desirable traits) is very challenging, difficult and time consuming without MAS.

Basically, there are two major MAS strategies applied in plant breeding program:

(i) Backcrossing for favorable alleles into elite germplasm, i.e. marker-assisted backcrossing (MABC)

(ii) Stacking multiple genes of different sources into elite breeding lines, i.e. marker-assisted gene pyramiding (MAGP). The success of MAS

Genetic markers associated with agronomic traits can be introgressed into elite crop genetic backgrounds via marker assisted breeding (MAB)

Successful applications of MABC and MAGP allow stacking of desirable traits into elite varieties to make them better adapted to climatic changes.

Successful implementation of MAS breeding in broad range of crops including barley, beans, cassava, chickpea, cowpea, groundnut, maize, potato, rice, sorghum, and wheat (64)

Biotechnology Cont'd

DNA sequencing and advent of genomics assisted breeding: In order to capture diversity of specific gene families within a large group, DNA samples can preferentially be enriched before sequencing. This approach can be adopted to define genetic variation in disease resistance gene repositories.

Sanger sequencing to study plant genomes is unfeasible due to low throughput and high sequencing costs. Subsequently, several sequencing platforms such as developed by Illumina, ABI, Life technologies, PacBio, Oxford Nanopore and Complete genomics were released commercially, changing the scenario of genome sequencing.

Rapid cost reduction in genome wide genotyping allows large scale assessment of crop species diversity to capture climate related traits. High SNP density approach like whole genome resequencing (WGR) & low SNP density approach like reduced representation sequencing (RRS) are majorly used. The variants identified by genotyping by sequencing (GBS) can be used for conventional QTL analysis and modern approach like genome wide association studies (GWAS). SNP genotyping have been widely used in many crops including wheat and Maize [72, 73]

Biotechnology Cont'd

Genome editing: a revolutionary tool in breeders' toolkit: Genome editing has enabled breeders to precisely add or delete any DNA sequence in the genome and has shown enormous potential to revolutionize the crop improvement in this very decade.

Some approaches like transcription activator-like effector nucleases (TALENs) and zinc finger nucleases (ZFNs) have been in the game for more than 2 decades.

However, type II clustered regularly interspaced short palindromic repeat (CRISPR)/CRISPR-associated protein (Cas) system from Streptococcus pyogenes developed in last decade has been most versatile tool in breeder's toolkit to introduce desirable or novel traits and accelerate development of climate smart crop varieties.

Genome editing has huge potential to accelerate the domestication of novel crops form CWR or minor crops with valuable traits for coping with extreme climatic events.

Biotechnology Cont'd

DNA free genome editing (DFGE): Conventional genome editing using recombinant DNA (rDNA) leads to random host genome integration and can generate undesirable genetic changes or DNA damage.

DFGE takes care of such critical issues along with reduced risk of off-targets.

Initially, it was successfully deployed in rice and tobacco with transfection of protoplast with CRISPR-Cas9 ribonucleoprotein (89).

A particle bombardment mediated DFGE approach has been developed in wheat and maize [90, 91].

Biotechnology Cont'd

Base editing: It is evident that a single base change can cause variation in the elite traits, so there required an efficient technique to cause precise and efficient point mutations in plants.

CRISPR-Cas9 driven base editing is new approach which accurately transform one DNA base to another without repair template. E.g. Cytidine deaminases convert cytosine (C) to uracil (U), which is treated as thymine (T) in subsequent DNA repair and replication, thus creating C•G to T•A substitution.

It has been utilized in wheat, maize and tomato and can be quite useful for gene functional analysis and therefore can assist breeding for better stress adapted varieties (94)

Biotechnology Cont'd

Prime editing: Another latest milestone in this genome engineering era called prime editing allows introduction of all known 12 base to base conversions in addition to mutations such as insertions and deletions using prime editing guide RNA (pegR) (95).

This promising approach opening up numerous possibilities for effectively targeting and modifying desirable genome sequences to accelerate functional genomics and introduction of genes for adaptation to diverse climates can boost breeding for climate smart crop varieties in near future [96].

In this rejuvenated plant mutagenesis breeding era, genome editing can be used in functional genomics for the identification of candidate genes for climate related agronomic, physiological and phonological traits, which can be exploited for crop improvement in adaptation to changing climate.

Phenomics and Artificial Intelligence (AI): ***Optimizing the genetic gains***

Accurate prediction and selection of best lines for specific environment relies on breeders' ability to model an immensely complex system from web of genomic and phenomic data.

Omics technologies (genomics, transcriptomics, proteomics, metabolomics, phenomics, epigenomics and microbiomics) together with approaches to gather information about climate and field environment conditions have become routine in breeding programs now a days.

Breeders now have access to wide range of high-throughput sensors and imaging techniques for spectrum of traits and field conditions.

Integrating with phenomics and genomics, artificial intelligence technologies (by assisting with big data) can boost up the development of climate resilient crop varieties with enhanced yield potential and stability and improved tolerance to expected simultaneous environmental stresses (abiotic and biotic).

Phenomics and Artificial Intelligence (AI) - *Cont'd*

Field phenomics: Accelerated plant breeding for climate resilience is critically dependent upon high resolution, high throughput, field level phenotyping that can effectively screen among better performing breeding lines within larger population across multiple environments.

With advent of novel sensors (unmanned air vehicle-UAV), high resolution imagery and new platforms for wide range of traits and conditions, phenomics has been elevating the collection of more phenotypic data over the past decade.

High throughput phenotyping (HTP) allows the screening for plant architectural traits and early detection of desirable genotypes. It enables accurate, automated and repeatable measurements for agronomic traits (seedling vigor, flowering time, flower counts, biomass and grain yield, height and leaf erectness, canopy structure) as well as physiological traits (photosynthesis, disease and stress tolerance).

With high throughput phenotyping facilities and the recent deep learning (DL), phenomics can be adopted as novel tool for studying plant genetics and genomic characterization enhancing the crop breeding efficiency in era of climate change

Conclusion

In the face of ongoing and projected climate change, including higher temperatures and more erratic climate events across extensive regions over the globe, breeding of crop plants with enhanced yield potential and improved resilience to such environments is crucial for the global food security.

In order to be able to make considerable contribution in climatic resilience, research attention is indispensable for currently underutilized crop species.

The concept of smart breeding which largely depends upon generating large breeding populations, efficient high throughput phenotyping, big data management tools and downstream molecular techniques is a potential innovation to tackle the vulnerability of crop plants to changing climate.

Plant breeders need to do more in developing new skills in multi-genotypic breeding and see plant breeding as a business which must ensure a ‘return on investment’ and produce goods (new varieties) that ensure a convergence of interests of different economic stakeholders.

The wide disparity between the experimental and farmers’ yields has undoubtedly eroded the farmers’ confidence in varietal generations especially in Nigeria. Therefore associations of breeders with farmers, in their roles as intermediaries or full partners, must be strengthened and simplified to restore the confidence. A superimposed artificial selection between the breeders and the farmers, with criteria that may change from location to location and with time, could be of tremendous help.

All stakeholders, including governments, must considerably play their roles if we are to develop a resilience strategies to climate change now and in the future.