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19th INAUGURAL LECTURE

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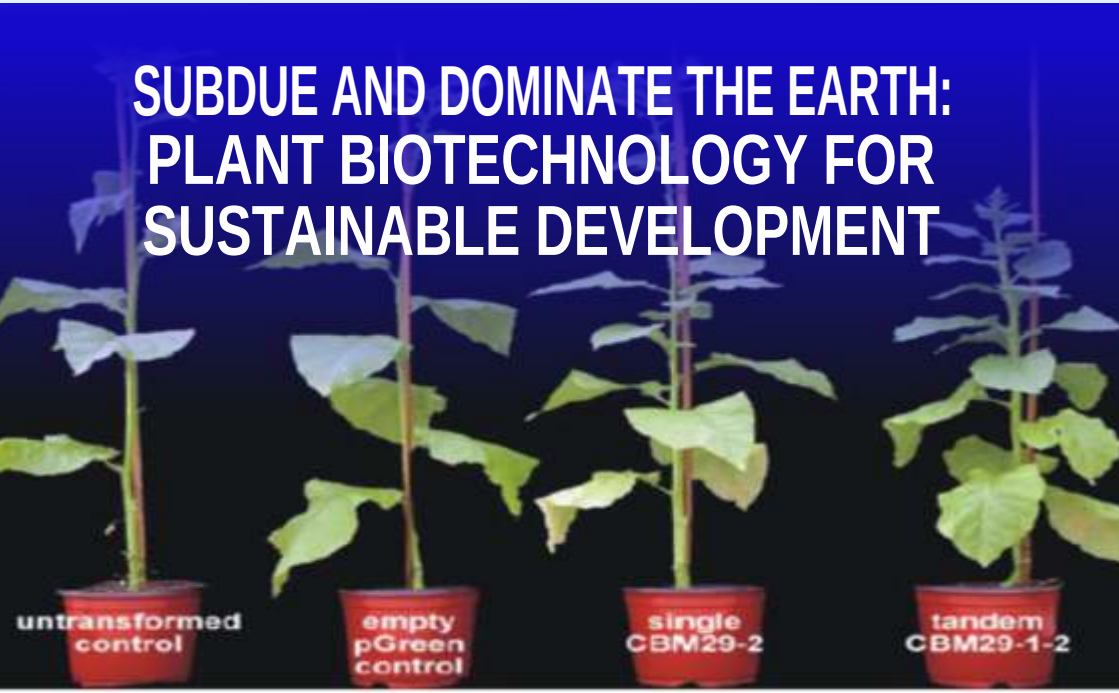

OLAWOLE O. OBEMBE

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SUBDUE AND DOMINATE THE EARTH: PLANT BIOTECHNOLOGY FOR SUSTAINABLE DEVELOPMENT

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PREAMBLE

Protocol

The Chancellor, The Vice-Chancellor, The Deputy Vice-Chancellor, The Ag. Registrar and other Principal Officers of Covenant University; The Dean, College of Science and Technology, Deans of other Colleges and School of Postgraduate Studies; Directors, Professors and other members of Senate; The Head, Department of Biological Sciences; Heads of other Departments, Academic, Administrative and Technical staff of the University; Members of my nuclear and extended family, Distinguished invited guests and friends, Gentlemen of the print and electronic media, Kings and Queens in Hebron, Ladies and Gentlemen.

It gives me great pleasure to stand before this beautiful audience to present the 19th Inaugural Lecture of this great citadel of learning. It is indeed a great privilege to be the first Covenant University Professor of Plant Biotechnology as well as the first professor in my town (i.e., Igangan-Ijesa, in Atakunmosa East Local Government Area of Osun State, Nigeria) to give an Inaugural Lecture. Igangan had produced a professor before me but the late Rev. Fr. Prof. Makanjuola Ilesanmi, though full of great intellect and sterling academic achievements, did not have the opportunity to present his Inaugural Lecture before his death. As such, I bless God for His mighty hand upon me and for keeping me hale and

hearty to see this glorious day. It is for this reason I will be starting my lecture with a song of appreciation to God.

Laarin opo eda nile aye
Laarin opo eniyan tosan jumilo (2x)
Oti kamiye o, lati ma yin o
Tani mba fi olorun mi we.
Aa oye ki ndupe, Ope ye o, baba (2x)
At'emi o, at'ara ile mi
Awa laye, atun wa laaye
Aa oye ki ndupe, Ope ye o, baba

From an early age, I have been fascinated by plants. Being very close to my mummy back then, I was always trying to replant the stumps of Amaranthus vegetable (Tètè) in used tins of peak milk and pronto (a cocoa beverage) at the back of the house after mummy had finished picking the leaves therefrom. I would make sure I picked all pepper and tomato plants I saw growing on my way from school to be transplanted inside my tins. It was such a joy to see the first flower on my tomato and then the pepper. Though the Amaranthus did not develop luxuriantly green leaves like the ones mummy used for cooking, I was still thoroughly satisfied to see them flushing at the nodes.

I was inspired by these experiences to develop interest in Biology since my secondary school days, in fact it was my best subject

then. This interest was sustained and culminated in my admission to study Botany (the study of plants) at the Obafemi Awolowo University (OAU) in 1986. The support I received from my mum (who is my first and best research collaborator) when I was conducting my final year research project stimulated my interest in academic research. This is because the project, supervised by Dr. Benjamin Ayisire, exposed me to the plant research involving the use of Plant Growth Regulators and it was published as my first academic publication in 1997 (Ayisire *et al.*, 1997). As such, I did not have to struggle with job hunting after my NYSC, as I proceeded straight to enrol for my Masters programme in Botany and at Ife.

It was not until I started the Masters programme that I began to have passion for Plant Biotechnology. I trained under a foremost and renowned Professor of Plant Physiology, Prof. A. Craig Adebona of Botany Department, OAU, Ife, who introduced me to the fundamental aspect of Plant Biotechnology, known as the Plant Tissue Culture. The M.Sc experience gave me the opportunity to be equally mentored by a Plant Tissue Culture Scientist of the Cocoa Research Institute of Nigeria, Prof. Edward Babatunde Esan, who willingly served as my unofficial co-supervisor. The prospect of growing new plants from any part thereof, aside the seed, really thrilled me. It was that enthusiasm that gave me breakthrough in my M.Sc project, out of which I published three

journal articles (Obembe *et al.*, 1999; Obembe, 2000a; 2000b).

Even though I had been an Assistant Lecturer for three years at the University of Agriculture, Abeokuta, I heard of the technology that drives the modern-day biotechnology, which is the Recombinant DNA Technology (Genetic Engineering) for the first time, when I attended a training workshop organized by the University of Nigeria Nsukka on behalf of the International Centre for Genetic Engineering and Biotechnology in 1997. I was extremely overwhelmed by the possibility of working at the molecular level of the Deoxyribonucleic acid (DNA), which is the primary genetic material of the cell. I found this more fascinating and challenging than my Plant Tissue Culture experience and consequently, I resolved to pursue a Ph.D degree in Plant Genetic Engineering. It was this dream that led me to the International Institute of Tropical Agriculture (IITA), Ibadan and I was offered a Ph.D position at the Biotechnology Research Centre (now Bioscience Research Centre) in 1998. At IITA, I was privileged to work on cowpea genetic transformation under the supervision of Prof. Jesse Machuka of blessed memory. I pursued this assignment with huge commitments and great sacrifices. Even though, the experience did not lead to the award of a Ph.D degree, God was good and faithful to give certain measure of success, which culminated in four (4) scientific publications (Obembe *et al*., 2000a, 2000b; Machuka *et al*., 2002; Obembe *et al*., 2005).

The hope of obtaining a Ph.D in Plant Biotechnology was kept alive when in April 2001, the Government of the Netherlands offered me a research fellowship to start a fresh Ph.D programme in the laboratory of Plant Breeding, Wageningen University and Research Centre (the world's best Agricultural University). It would interest you to note, Sir, that I travelled to the Netherlands, against all odds, to take up this offer when my daughter was just 2 months old. Life and studies in the Netherlands were so fulfilling as I eventually defended my Ph.D thesis entitled "Bio-engineering cellulose and hemicellulose networks in plants", under the supervision of Professors Evert Jacobsen, Richard Visser and Jean-Paul Vincken on January 30, 2006 (Obembe, 2006). My experiences in Wageningen defined who I am today. Aside the world-class research exposure, I was also privileged to attend several international meetings (seminars, workshops and conferences) within the Netherlands and in six other countries (UK, US, Germany, Italy, France, Belgium).

My relentless passion for Plant Biotechnology research made me to search for and got a UNESCO Postdoctoral Research Fellowship placement at the International Centre for Genetic Engineering and Biotechnology, New Delhi, India. Chancellor Sir, I would like to state here, with a deep sense of appreciation that, by providence, I was the first postdoctoral beneficiary in Covenant University. The postdoc experience was most rewarding as it gave

me the opportunity to publish my most successful article (with 131 Scopus citations). The article, which was entitled "Advances in Plant Molecular Farming" was published in one of the best journals of Biotechnology in the world, Biotechnology Advances, with a 98 percentile and an Impact Factor of 11.8 (Obembe *et al*., 2011).

What is Biotechnology?

The term "Biotechnology" was originated by Hungarian engineer, Karl Ereky in 1919. There are two root words in Biotechnology: *Bio*, which means the utilization of biological processes, and *Technology*, which means to make useful products or solve problems. As such, biotechnology is broadly defined as "application of living organisms or the products of living organisms, for human benefit (or to benefit human surroundings), to solve problems or make products*"*. Another simple and widely accepted definition of Biotechnology is "any technique that uses living organisms or parts of organisms to make or modify products, to improve plants or animals, or to develop micro-organisms for specific use".

Brief History of Biotechnology

Humans have been using organisms for their benefits in many processes for several thousands of years. The Chinese, Greek,

Romans etc. have been involved in biotechnology since nearly 2000 B.C. A process as simple as domestication of animals such as cattle and sheep for use as livestock is an example. Fermentation through the exploitation of microorganisms to make bread (yeast), cheese, yoghurts (Streptococcus thermophilus) and alcoholic drinks including wine and beer is another example. Humans for thousand years, have utilized selective breeding as a biotechnology application to improve crop and livestock production for food purposes (www.coursehero.com, internet source). By selecting animals and plants with good quality traits, humans are preserving organisms with beneficial genes and leveraging on their genetic potential for man's benefit. This traditional form of biotechnology was what developed into classical breeding (crossing) that we have today, and involves crossing individuals with desirable characteristics (e.g. yield) and selecting among the progeny. Genes recombine in a random fashion and finding superior progeny needs excellent management since it is a numbers game and genotype is often masked by environmental influences. The discovery of natural mutants within plant species led to the study of mutation breeding. Mutations of plant's DNA can be achieved via a method known as mutagenesis, which involves the use of chemicals or radiation to modify an organism's genetic information. Resultant plants may possess novel and desirable traits through the alteration of their DNA.

During this process, plant breeders must grow and access each plant from each seed produced. Then there was the discovery of the moving genes (Transposons), which are mobile DNA segments that move from one site to another on a chromosome. Barbara McLintock (1950) showed how transposon-mediated DNA modifications influenced the colour of maize kernels (www.econatics.co.za, internet source). One of the commonest uses of biotechnology is in the production of antibiotics, which are compounds synthesised by microorganisms, that inhibit the growth of some other microorganisms. Alexander Fleming found that the mold, *Penicillium* prevented the growth of *Staphylococcus aureus*, a bacterium, which in humans causes skin diseases. In 1950s, it was possible to purify large amount of antibiotics from many different strains of bacteria.

Watson and Crick (1953) uncovered the three dimensional structure of deoxyribonucleic acid (DNA), which consequently, enhanced the understanding of genetics and the functionality of genes (www.econatics.co.za, internet source). The discovery of the DNA structure has since revolutionised biology and has spawned the fields of gene cloning (identification, isolation and amplification of a gene of interest), genetic engineering (manipulation of an organism's genetic material to produce a desirable trait) and ultimately recombinant DNA technology (combination of DNA fragments from different sources). Recombinant DNA (rDNA) technology has greatly impacted

man's health and wellbeing through identification of several thousand genes that are associated with genetic diseases in humans. The definitive accomplishment of rDNA technology is the Human Genome Project, which was carried out to unravel the genes contained in the entire human genome and to precisely map their locations to each of the 23 human chromosomes. This breakthrough has led to the emergence of new field of study known as Genomic Medicine, which has provided limitless possibilities for developing novel diagnostic strategies for treating and curing human genetic disease conditions (Aworunse *et al*., 2018).

Types of Biotechnology

The Chancellor, Sir, there are diverse types of biotechnology, and are briefly explained hereafter. However, due to the scope of the lecture and my research experience in the last 25 years, I shall be focusing more on plant biotechnology.

Microbial Biotechnology

The use of yeast to make wine and beer is one of the ancient applications of biotechnology. By manipulating microbes such as yeast and bacteria, microbial biotechnology has developed more efficient organisms and enzymes for making or modifying foods, simplifying manufacturing and production processes, and making decontamination processes for industrial waste products removal more efficient. Another application of microbial biotechnology is in the leaching of oil and minerals from soil to increase mining

efficiency. Microorganisms are also used to mass produce high valued proteins used in human and veterinary medicine including growth hormone and insulin.

Bioremediation Biotechnology

This is the use of biotechnology to degrade a diverse kind of toxic and hazardous substances that contribute to environmental pollution. Bioremediation is being applied for cleaning up of many environmental hazards such as oil spills, domestic and industrial sewage treatment.

Animal Biotechnology

Animals can be utilized as bioreactors to make important products. For example, chicken, sheep, cattle, and goats are now being used as medical sources of drug proteins such as antibodies, which are proteins that help body cells to recognize and destroy foreign materials. Other therapeutic proteins have also been obtained from the animals, the production of which has been scaled up through the creation of female transgenic animals that express these proteins in their breast milk. Animals have been used in basic research such as the gene knockout, in which one or more genes are disrupted, leading to the unravelling of the gene function. Animal cloning has been achieved with Dolly and many others but there are ethical concerns about further development despite the huge potential such as organ transplant to humans.

Forensic Biotechnology

DNA profiling and fingerprinting, a collection of techniques for distinguishing an organism based on its unique pattern of DNA, is a key tool in forensic biotechnology. The method has found diverse applications particularly in criminal investigations to include or exclude a person from suspicion based on DNA evidence, paternity cases to pinpoint a child's father, and for identifying human remains.

Aquatic Biotechnology

One of the oldest applications of aquatic biotechnology is aquaculture i.e., raising finfish varieties in controlled conditions for use as food sources. Nowadays genetic engineering is being exploited to produce disease-resistant strains of oysters and vaccines against viruses that infect finfish and salmon.

Medical Biotechnology

A number of biotechnologically-derived products such as recombinant proteins and drugs are now being manufactured for human medical applications. It involves a broad range of human medicine from preventive to diagnostic to curative medicine. The human Genome project has resulted in new methods for genetic analysis to detect defective genes and the resulting genetic disorders. Stem cells technologies are some of the newest, most promising aspects of medical biotech.

Regulatory Biotechnology

Biotechnology business involves regulatory processes that govern the industry. The two important regulatory processes are quality

assurance and quality control to evaluate the final products based on specific guidelines designed to maximize their safety and effectiveness.

What is Plant Biotechnology?

Plant biotechnology can be defined as the introduction of characters of interest into plants via genetic modification to adapt them for specific needs or opportunities. It is based on the phenomena of cellular totipotency and genetic transformation (Vasil, 2008). Genetic manipulation of plants has been used for over 30 years to produce genetically modified crops with modulated growth traits for greater food yields, tolerance to cold temperature, drought resistance, resistance to insect pests and herbicide tolerance. Plant biotechnology is now being explored to provide bio-ethanol from corn, and agricultural waste with high cellulose content, thereby contributing to less dependence on fossil fuel. The utilization of plants as biofactories for the production of biopharmaceuticals is an application of plant biotechnology known as molecular pharming (Obembe *et al*., 2011). Moreover, plants are now being engineered to enhance their photosynthetic efficiency and growth (Mueller-Cajar, 2018; Salesse-Smith *et al*., 2018).

Techniques used in Plant Biotechnology

Marker -Assisted Selection

Marker-Assisted Selection also known as molecular breeding speedily identifies genes associated with characters of interest, thus accelerating their introduction into crop lines for growers. It involves the use of molecular markers such as single nucleotide polymorphisms (SNPs) and microsatellites (Murphy, 2004). These markers can be employed to identify the presence of desirable traits in a number segregating populations used in a plant breeding programme (Figure 1, Murphy, 2004). For instance, if a good trait such as resistance to a disease can be associated with a specific marker (Murphy, 2004), several young plantlets can be evaluated for the presence of the character without necessarily growing all the plants to maturity, or performing expensive, laborious and time-consuming biochemical or physiological

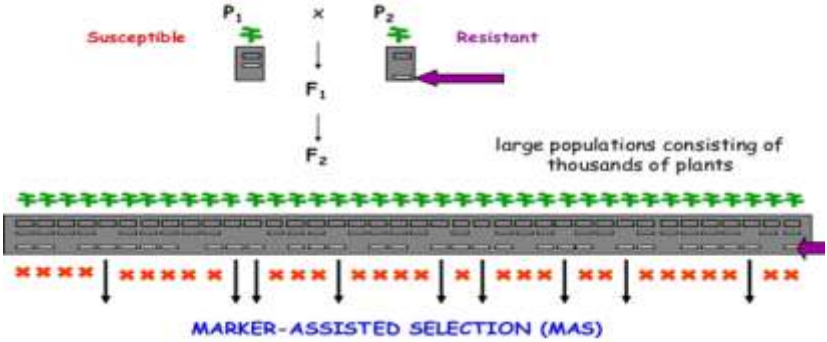

Figure 1: Marker-assisted selection, a method whereby phenotypic selection is based on DNA markers

Tissue Culture

The technology produces copies of plants of interest without the need of seeds. It permits the rapid production of high quality, disease-free and uniform planting materials. Indeed, tissue culture is the limiting step to most genetic transformation procedure whereby the cell that has been transformed with the transgene needs to regenerate into a whole viable plant. Other techniques include embryo rescue, which has been used for the introgression of traits such as disease resistance from wild relatives into elite breeding lines of crops. Additionally, plant tissue culture methods can be applied for mass clonal propagation or micro-propagation (Figure 2). This is *in vitro* multiplication of plants that entails the application of plant growth regulators (PGRs) to induce meristematic activity of lateral or adventitious buds of the plant's tissue or organ cultured on growth medium, leading to the formation of multiple shoots.

Figure 2: In vitro clonal propagation of plants (Source: https://thumbs.dreamstime.com/z/plant-tissue-culture-growth-tissues-cells-separate-organism-typically-facilitated-via-use-43823192.jpg)

Also, plant tissue culture techniques include protoplast fusion. Protoplasts are cells that have their cell walls removed either by enzymatic or mechanical means. Protoplasts can be manipulated in a number of ways for the purpose of plant breeding. These include production of hybrid cells through cell fusion and the use of protoplasts to facilitate gene transfer into plant cells (Figure 3), which can then be grown *in vitro* via tissue culture techniques (www.econatics.co.za, internet source). This technique has been used widely for interspecific and intergeneric hybridization.

Figure 3: Protoplast fusion (Source:https://static.turbosquid.com/Preview/2014/09/25__11_06_44/Protoplastfusion_05.pngfcedb9e8-9b74-4f9a-8a6c-dad8b70302daOriginal.jpg)

Genetic Engineering

Genetic engineering in plants involves the introduction of DNA into plant cells in such a way that the foreign genetic information would be expressed in the transformed cells (Figure 4). This

ensures that only required genes with known useful benefits are integrated into crops (www3.bio.org, internet source). The resulting transgenic (genetically modified, GM) plants certainly have some advantages over those obtained through sexual process or by somatic hybridization. For example, genetic engineering can achieve in a short time what would take several years with selective breeding. In several cases, the advantages derived from plant genetic engineering would not be possible through any other means.

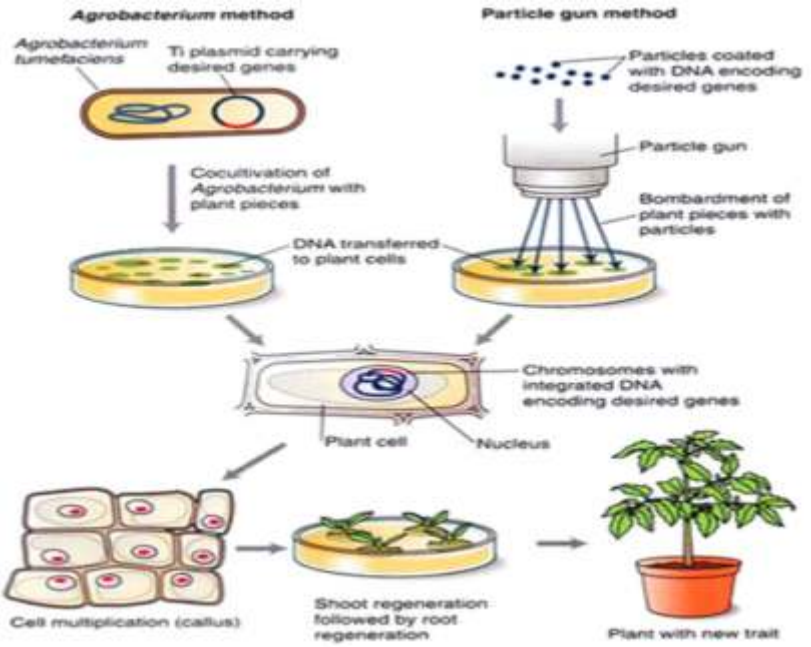

Figure 4: Scheme of plant genetic transformation via Agrobacterium and Gene gun (Source: http://www.flickriver.com/photos/biotechnology/2978906116/***)***

The methods used in plant genetic engineering often involve tissue culture regime whereby transformed cells/tissues are grown in culture to regenerate into transgenic plants. Hence, a transformation procedure must be compatible with regeneration protocols for an overall success. The plant regeneration approaches used in plant genetic transformation can either be organogenesis or somatic embryogenesis.

Somatic embryogenesis

This process involves the production of embryo-like structures from somatic tissues, which subsequently can develop into whole plants in a way that is similar to zygotic embryos. The production of somatic embryos can be direct, involving the formation of embryos from a cell or a group of cells without an intervening callus stage or indirect, in which case, callus is first produced from the somatic tissues of explants, followed by the production of embryos from the callus tissue. This approach has been shown to be the best for coupling with the genetic transformation of cotton (Obembe *et al*., 2011). Usually, somatic embryogenesis proceeds in two phases: an initiation phase, which involves the use of high concentrations of 2,4-Dichlorophenoxylacetic acid (2,4-D) and an embryo production phase, in which embryos are produced in a medium with little or no 2,4-D (Figure 5).

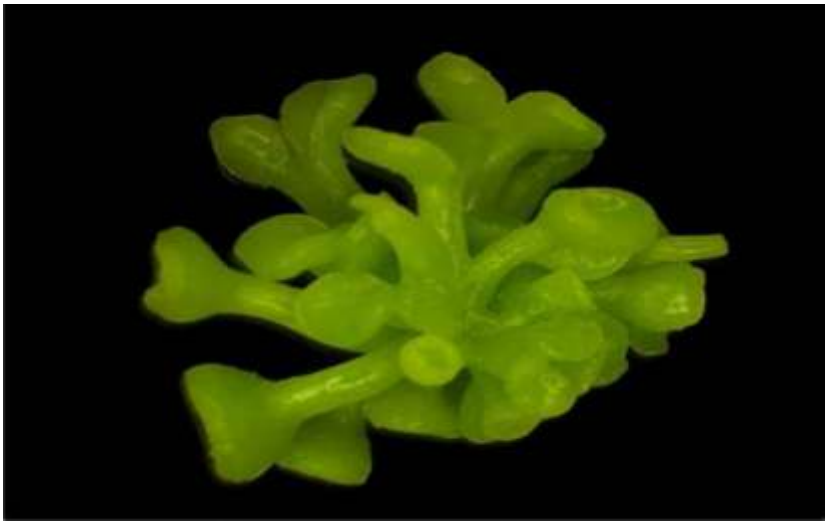

Figure 5: Soybean somatic embryos (Source: http://www.scienceasart.org/soybean-somatic-embryos)

Organogenesis

This approach relies on the production of adventitious organs either directly from an explant or from a callus culture. Organogenesis is possible because of the inherent plasticity of plant tissue, which can be modulated by modifying the composition of the medium, especially the auxin:cytokinin ratio. Usually, shoot induction is achieved by increasing the cytokinin:auxin ratio of the culture medium. The shoot can then be rooted relatively simply. We have widely used this approach for many crop species, including cowpea (Obembe, 2008a), potato (Obembe *et al*., 2008), cotton (Obembe *et al*., 2010; 2011),

tobacco (Obembe *et al.*, 2007a; 2007b), pumpkin (Obembe *et al.*, 2017a), wild lettuce (Obembe *et al.*, 2017b) and *Solanecio biafrae* (wòròwó) (Figure 6).

Figure 6: Multiple shoots formation in Solanecio biafrae* (wòròwó) *(unpublished)

Different Methods used in Genetic Engineering

***Agrobacterium*-mediated genetic transformation**

Natural genetic transfer occurs in plants when a wound is infected with the soil bacterium, *Agrobacterium tumefaciens*. The bacterium carries a large extra-chromosomal circular DNA

known as plasmid that causes an unrestrained proliferation of cells (tumours) in plants, a condition called the crown gall disease (Figure 7).

Figure 7: Crown gall on Euonymus (burning-bush) caused by Agrobacterium tumefaciens (Courtesy R.L. Forster)

Consequently, the plasmid is referred to as tumour-inducing (Ti) plasmid. The Ti plasmid has given the biotechnologist an ideal vehicle for transferring DNA, using for a start, the leaf fragment

technique (Figure 8). This involves cutting small leaf discs from a leaf and exposing them to modified *Agrobacterium* cells containing recombinant plasmid that harbours the desired genes to be inserted into the plant. During the exposure, the Ti plasmid transfers the desired gene to be inserted into the plant cell and integrates same into the genome of the recipient cell. The infected leaf explants are then cultured on shoot induction medium amended with PGRs as well as appropriate antibiotics or chemicals that will inhibit the growth of non-transformed cell and allow for selection and growth of only transformed cells.

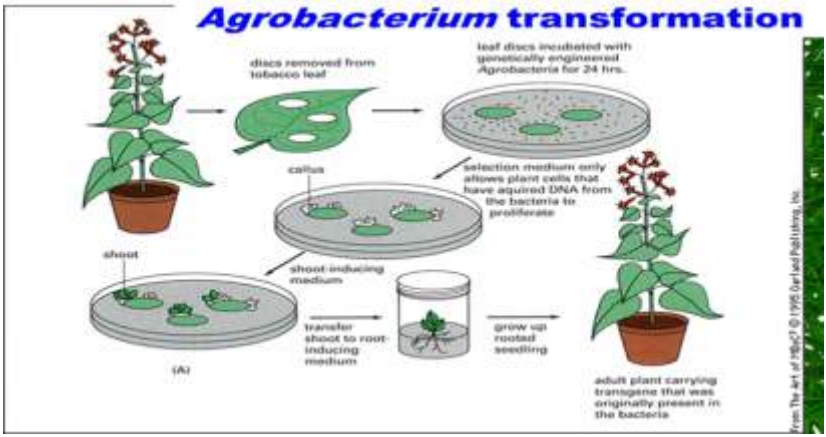

Figure 8: Agrobacterium-mediated transformation (Source: http://slideplayer.com/slide/6113710/)

Gene Guns (particle bombardment)

This is another method of inserting genes into crops that are difficult to be transformed by *Agrobacterium*. Gene gun (Figure

9) is an example of direct gene transfer method, which is used to discriminate between methods that rely on *Agrobacterium* (indirect method) and those that do not (direct methods). Gene gun is used to literally blast tiny metal particles coated with DNA into plant cells. It is used to shoot naked DNA at the plant cell, aiming the nucleus or the chloroplast. In either case, the transformed cells that carry the introduced gene must be identified. This is achieved by combining the gene with a gene that makes the cell resistant to certain antibiotics. These are called the selectable marker genes or reporter gene. After gene gun procedure, the cells are grown on shoot induction medium containing appropriate antibiotics, which would allow only the genetically transformed cells to survive and grow into mature plants.

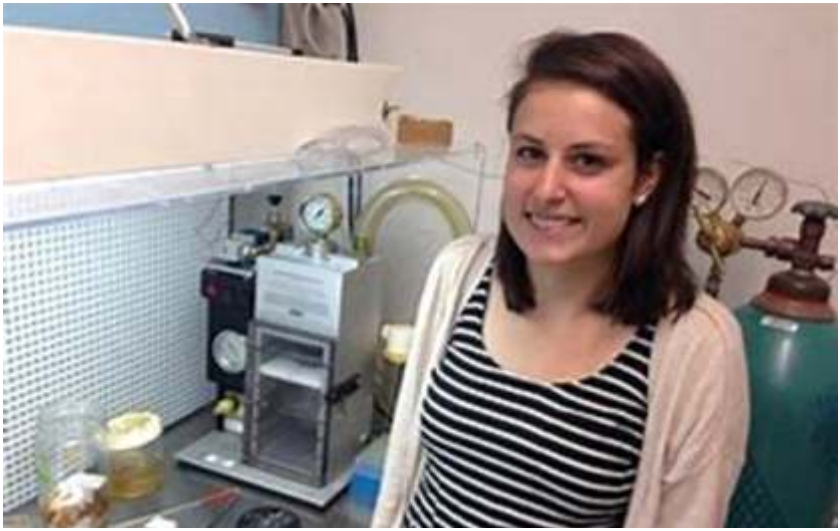

Figure 9: A Bio-Rad Biolistic Particle Bombardment (Gene Gun) Machine (source: https://www.nhpr.org/post/unh-undergrad-seeks-produce-first-genetically-decaffeinated-tea-plant)

Other direct gene transfer methods include:

Polyethylene glycol (PEG)-mediated transformation

Naked DNA can be used to transform protoplasts. This is achieved by treating protoplasts with PEG in the presence of divalent cations like calcium. The PEG and the cations disrupt the protoplast cell membrane and makes it pervious to naked DNA. Once inside the protoplast, the DNA finds its way into the nucleus and is integrated into the cells genetic material.

Electroporation

This method is used to introduce DNA into plant cells and protoplast. The plant material is incubated in a buffer solution containing the DNA and subjected to high voltage pulses generated by the electroporation device (Figure 10). The DNA then migrates through the high voltage-induced pores in the cell membrane and integrates into the genome. However, the plant material used for electroporation may require specific treatments such as pre- and post-electroporation incubations in high osmotic buffers.

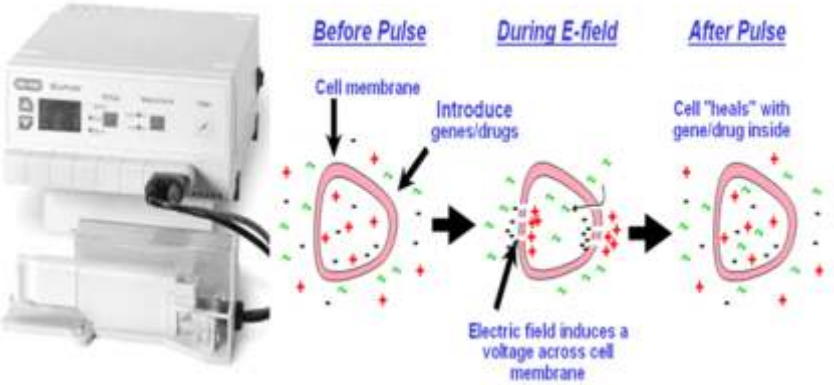

Figure 10: Bio-Rad electroporation Machine, Mode of action of electroporation (Source: http://www.bio-rad.com/, https://www.philpoteducation.com/mod/book/view.php?id=2994&chapterid=3059#/***)***

Silicon carbide fibres – WHISKERS

Here, plant materials such as embryos, embryo-derived calluses and cell suspension cultures are introduced into a buffer containing silicon carbide fibres and DNA, and then vortexed. The fibres, which are 0.3 – 0.6 µm in diameter and 10 -100 µm in length penetrate the cell wall and membrane, thus enabling the DNA to access the inside of the cell, as illustrated in Figure 11.

Figure 11: Scheme of whisker-mediated transformation of soybean (Source: Khalafalla et al., 2010)

Liposome-mediated gene transfer

Liposomes are microscopic lipid compounds, which are produced when phospholipids are dispersed in an aqueous phase. Liposome can be made to entrap DNA and then made to interact with cells in such a way that plasmid will eventually be transferred into their nucleus (Figure 12). PEG can be used to enhance the efficiency of DNA delivery.

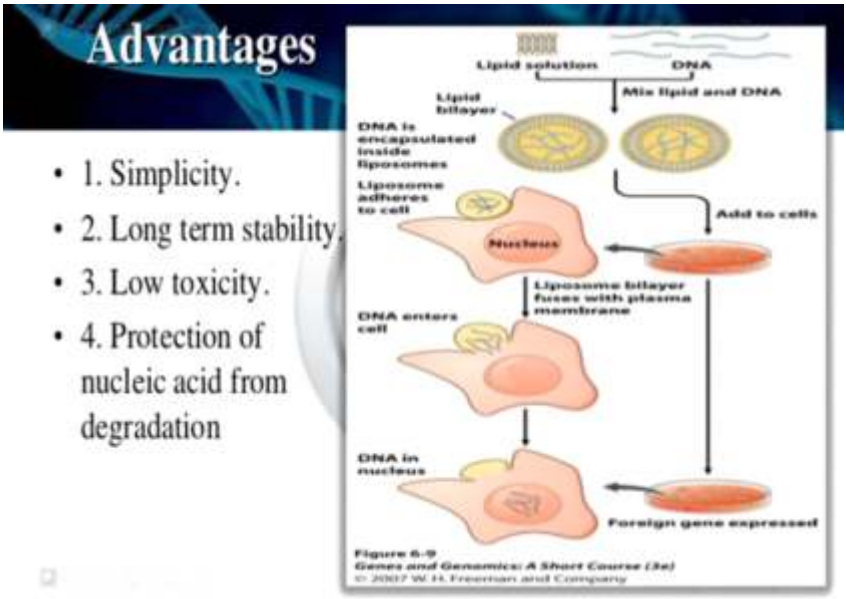

Figure 12: Liposome-mediated transformation

Microinjection

Involves surface attachment of protoplasts on a slide by embedding in agarose, using a holding pipette. The DNA is transferred by injecting it with microneedles into the surface-attached protoplasts (Figure 13). Microinjected protoplasts are then cultured following standard procedures. In addition to protoplasts, microinjection has been applied to single cells, pollen tubes and immature embryos.

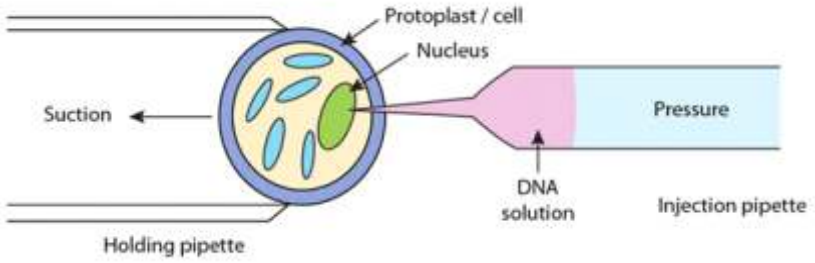

Figure 13: Microinjection technique (https://nptel.ac.in/courses/102103016/module3/lec24/3.html)

RNA Interference (RNAi)

The RNAi is a technology for silencing the function of specific genes (www3.bio.org, internet source) such that the proteins they encode are not expressed. RNAi mechanism, in nature is mediated by few molecules of interfering RNAs which block the expression of a target gene (Figure 14).

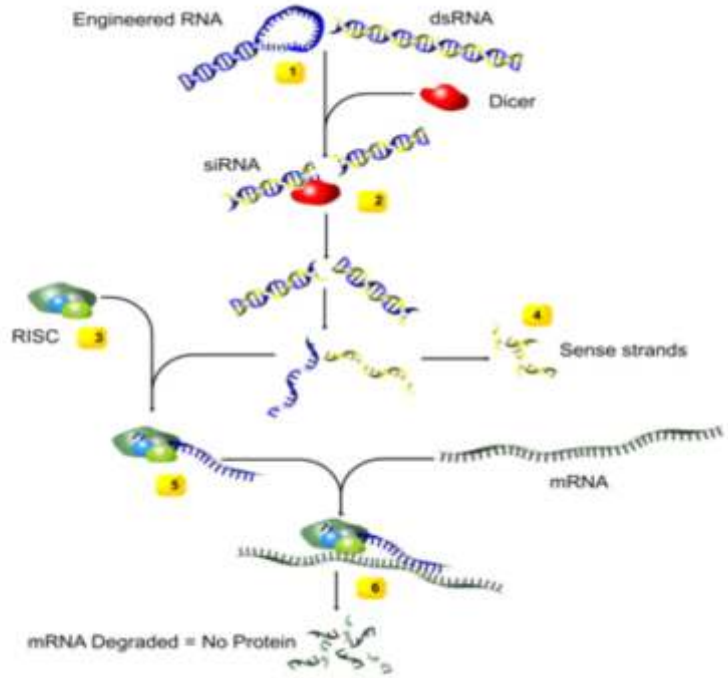

Figure 14: RNAi mode of action (Source: http://www.isaaa.org/resources/publications/pocketk/34/)

Modification of genes by these small interfering RNAs is one of the mechanisms by which plants respond to the environmental stress. This natural capability has been developed into a technology that has been widely used in producing plants with pest resistance (Mao *et al*., 2007), disease resistance (Fritz *et al*., 2006), improved quality (DeJong *et al*., 2009), and different abiotic stress tolerance (Sunkar and Zhu, 2004; Zhao *et al*., 2007; Arenas-

Huertero, 2009).

Gene editing Tools (CRISPR-Cas9)

CRISPR/Cas is a type of adaptive immunity in prokaryotes, which functions as a mechanism to degrade invading exogenous nucleic acids from plasmid or phage, and was first reported in 1987 (Ishino *et al.,*1987). This natural ability of the bacteria to defend themselves against viral invasion has been developed into the site-specific gene editing tool called the CRISPR/Cas system (Cong *et al*., 2013; Mali *et al*., 2013). The technology has been deployed to edit genes of several plant species in very precise manner (Figure 15, Jiang *et al*., 2013; Wang, 2014; Jacobs, 2015; Lawrenson *et al*., 2015).

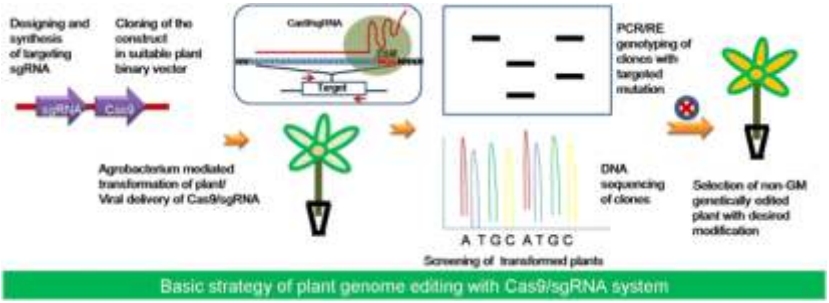

Figure 15: The CRISPR/Cas genome-editing tool in crop improvement (Source: Khatodia et al., 2016)

Lately, adenine base editors (ABEs), which comprise of Cas9 nickase and engineered transfer RNA adenosine deaminases

derived from *Escherichia coli*, have been developed for producing efficient and precise A-to-G conversion in the cells of higher eukaryotes, including plants (Figure 16, Beum-Chang *et al*., 2018; Gaudelli *et al*., 2017). This technology has been applied to generate transgenic *Arabidopsis* and *Brassica* plants with delayed flowering and albino phenotype, opening new vistas for plant biotechnology and genome engineering (Beum-Chang *et al*., 2018).

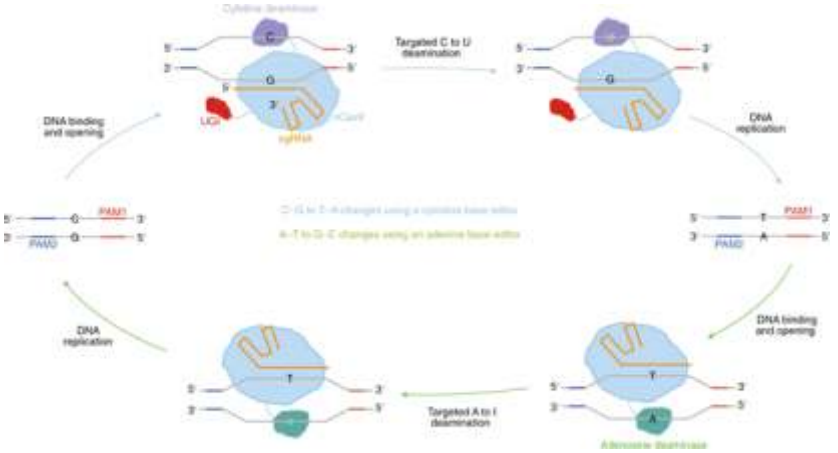

Figure 16: Adenine Base Editors precisely alter plant genomes without creating a DNA double strand break (Source: Shan Q. and Voytas, 2018)

The title for this Inaugural Lecture was inspired by the 16th Inaugural Lecture of Covenant University, which was delivered

by the late Prof. Patrick Edewor in September 2018, and entitled "Be Fruitful, Multiply, and Replenish the Earth: The Motivation, the Costs and the Gains". Consequently, my lecture is hereby presented to delve into the concluding part of the mandate that was given to Adam and Eve in Genesis 1:28. Hence, I shall be speaking to the title "Subdue and Dominate the Earth": Plant Biotechnology for Sustainable Development.

INTRODUCTION

The Chancellor Sir, the world population has been projected to increase from the present 7.6 to 9.7 billion by the year 2050. Currently, Africa has the highest annual population growth rate. An estimated 50% of the world population growth would be contributed by Africa, as the continent doubles its present population of 1.28 billion to 2.5 billion. By implication, Nigeria, which is the most populous African country has been predicted to double the present 191 million population to 411 million (Figure 17). Interestingly, this population would make Nigeria the 3rd most populous nation on the earth after China and India.

Figure 17: PRB projects Nigeria to have the third largest population in the world by 2050

It is noteworthy that while the world's population is increasing phenomenally in fulfilment of the mandate at creation, the size of the planet earth remains fixed and its resources also remain finite. This challenge has its effect on socio-economic development and the overall quality of life. The 16th inaugural lecturer concluded that rapid population growth and over-population lead to poverty, low standard of living, ill-health, malnutrition and environmental degradation, high rate of unemployment and high rate of crime. He further stressed that owing to the high fertility rate in Africa, there is a preponderance of young persons and consequently, a high dependency burden, which serves as an impediment to the realization of socio-economic development goals (Edewor, 2018). It is, however, not surprising to note that Nigeria has one of the highest fertility rates in Africa, 5.5% (PRB, 2017).

Plants are pivotal to the existence of life on the earth and in situations whereby population growth is exceeding food production, agriculture is as never before crucial to the economies and environments of the world. Modern agriculture must meet the demands of the ever-increasing population and the expectations of improved living standards, in the presence of frightening harmful consequences of diminishing arable land and environmental pollution (Rosu *et al.,* 2017). Plant biotechnology offers the world significant opportunities to subdue and dominate over the challenge of ever-growing demands for food, feed and fibre

production (Murphy, 2004), as well as the need for good health and well-being (Obembe *et al.,* 2006; Obembe, 2010); ensuring more efficient use of the world's limited resources and consequently contributing to **sustainable development**.

What is Sustainable Development?

Sustainable development is broadly defined as the economic development that is carried out without the depletion of natural resources. It can also be described as the development that meets the needs of the present, without compromising the ability of future generations to meet their own needs (Brundtland Report, 1987, http://www.un-documents.net/our-common-future.pdf), guaranteeing the balance between economic growth (economic sustainability), care for the environment (environmental sustainability) and social well-being (social sustainability). Furthermore, sustainable development can be described as the organizing principle for meeting **human development goals** while simultaneously preserving the capacity of natural systems to supply the ecosystem services and natural resources on which the society and economy depend (https://en.wikipedia.org/wiki/Sustainable_development).

What are Human Development Goals?

The United Nations Development Programme (UNDP) defines

human development as "expanding the richness of human life, rather than simply the richness of the economy in which human beings live". It is a strategy that is centered on people, and their opportunities and choices" (http://hdr.undp.org/en/humandev). It pays particular attention to improving the lives people lead as opposed to the assumption that economic growth will lead, ultimately, to better well-being for all. Growth in income is considered as a means to development, rather than an end in itself (http://hdr.undp.org/en/humandev). It has to do with giving people more freedom to live the life they value. This means developing people's capabilities and giving them an opportunity to utilize them. The three essential capabilities (foundations) for human development are for people to lead long and healthy lives, to have access to education and to achieve decent standard of living (https://www.unrwa.org/who-we-are/our-leadership). If these basic capabilities are not achieved, many choices will not be available, and many opportunities will remain unreachable.

What are Sustainable Development Goals?

The Sustainable Development Goals (SDGs), also known as the Global Goals, are a universal call to action to protect the planet, end poverty, and ensure that all people enjoy prosperity and peace (http://www.undp.org/content/undp/en/home/sustainable-development-goals.html). The 17 SDGs and 169 targets focus on

the 5 Ps of: planet, people, prosperity, peace and partnership, and is established on the Millennium Development Goals (MDGs) to achieve a more sustainable and better future for all. Chancellor Sir, this inaugural lecture aims at interrogating the potential impacts of plant biotechnology on five of these SDGs that directly address the three capabilities for human development in Africa, and Nigeria in particular. These are SDGs 1 - No Poverty, 2 - Zero Hunger, 3 - Good Health and Well-being, 4 - Quality Education and 8 – Decent Work and Economic Growth.

SDG 1 and SDG 2 – No Poverty and Zero Hunger

According to the United Nations estimates, over 750 million people, or 11% of the world's population, still live in abject poverty. Poverty, by the way, is not limited to lack of resources and income that guarantee a comfortable livelihood. It manifests as hunger and malnutrition, limited access to education, healthcare and other basic amenities (http://www.un.org/sustainabledevelopment). Southern Asia and sub-Saharan Africa (SSA) are homes to a large number of the world's poorest people that subsist on less than $1.90 per day. Sadly, SSA contributes 42% of the world's extremely poor people. More sadly, almost 50% of Nigeria's population (86.9 million) is extremely poor and as such, has overtaken India as the poverty capital of the world (Figures 18 and 19). This is impacting

negatively on the goal of ending extreme poverty by 2030.

Figure 18: Internally displaced women waiting for their food ration

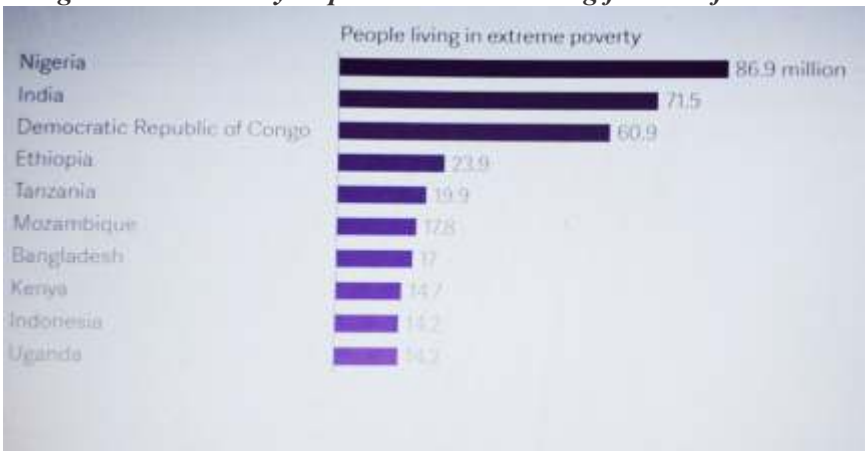

Figure 19: Nigeria has the highest number of extremely poor people in the world (Source: https://www.theatlas.com/charts/Hynnu6C-7)

Although city poverty is an increasing challenge, rural areas have the highest incidences of hunger and poverty. Majority of the people who dwell in the rural areas depend on subsistence

agriculture (Fan *et al.,* 2005), and as such, improved agricultural productivity is needed in such areas because of the population boom (FAO, January 22, 2017). Strategies to curb abject poverty in rural areas should, therefore, centre on improving agricultural productivity to enable the poor produce sufficient food for survival, while the remainder is marketed to generate income. There should be a drastic change in socio-economic policies that focus on agricultural and commercial development, with modern seed varieties playing a vital role, as they generate the healthiest crops (Sanchez, 2009). Almost all dietary calories are derived from cereal crops, notably maize and rice. These two crops constitute the major diet of over 75% of the world's population (FAO, 2009a). Maize contributes an ample amount of forage for livestock in developed countries like the US, and a number of countries in Africa where it is cultivated. In the short-term, the goal should be to bridge the yield gap in cereal crops (the gap between potential and actual yields) to subdue hunger, dominate health and generate economic prosperity. In the long-term, it will be necessary to apply the same approach to diverse vegetable crops and fruits, as well as cash crops such as coffee, cotton and tobacco (Yuan *et al.*, 2011).

A large number of the world's hungry people reside in developing countries, where 12.9% of the population is malnourished (Figure 20). In SSA, the rate of undernourishment is estimated to be 23%.

It is sad to note that 23 million children of primary school age in Africa go to school hungry. Food shortage is also responsible for poor development in millions of children, resulting in stunted growth (one in three in the developing countries) due to severe malnutrition. The rapidly degrading natural resources such as soils, forests, oceans, freshwater and biodiversity coupled with increasing incidences of droughts and floods, are making agricultural activities to be unproductive. Consequently, many rural people are barely surviving on their land and are being forced to migrate to cities in pursuit of better lives.

Figure 20: A hungry family (Source: https://www.nationalgeographic.com/foodfeatures/hunger/)

Multifaceted approaches that would increase the capacity for sustainable food production and agricultural productivity are imperative to help tackle the menace of hunger, more especially as an additional 2 billion people are anticipated to be malnourished by 2050.

African countries have the greatest potentials to benefit from modern agricultural biotechnology. This is due to the fact that about 70% of the population derive their livelihood from farming (ISAAA, 2017). The agricultural sector is the single largest employer of labour worldwide, providing income for 40% of the current global population. Agriculture contributes the largest source of income and jobs for poor rural households. Globally, five hundred million small farms, most of which are still rain-fed, produce about 80% of food consumed in major parts of the developing world. It is noteworthy that 65% of Africa's workforce is employed by the agricultural sector, which also contributes 32% of the continent's gross domestic product (GDP). Agriculture accounts for one-third of Nigeria's GDP (30%), and it is the leading employment sector, as it employs over two-third of the country's total workforce (http://www.fao.org/nigeria/fao-in-nigeria/nigeria-at-a-glance/en/). Thus, unlocking this vital sector holds the key to socio-economic transformation in African countries in general, and Nigeria in particular. Africa is home to over half of the world's uncultivated arable land and as such has

limitless opportunities to leverage on new technologies (ISAAA, 2017).

The Contributions of Plant Biotechnology to Subdue Poverty and Dominate Hunger

Plant biotechnology can assist to attain SDGs 1 and 2 via the adoption of high-yielding genetically modified (GM) crop varieties that are resistant to insect pests and diseases, weeds and adverse environmental conditions such as drought (Farre *et al.,* 2009). The aforementioned biotic factors (insect pests and weeds) can lower crop yields by up to 30%, especially in tropical developing countries where the weather conditions support the breeding and survival of insect pests and disease vectors. Additionally, adverse ecological conditions like flooding, drought and poor soil quality can have devastating effects on agricultural yield. Hence, the generation of crops that can survive under these conditions could assist in stabilizing crop production and hence contribute markedly to food security and economic progress (Christou and Twyman, 2004).

The insect pest challenge

Insect pest attacks on crop plants in the field or under storage inflict devastating losses worldwide (Figure 21). Nearly half of all the crops produced in the developing countries are lost to insect pest attacks (Christou *et al.*, 2006).

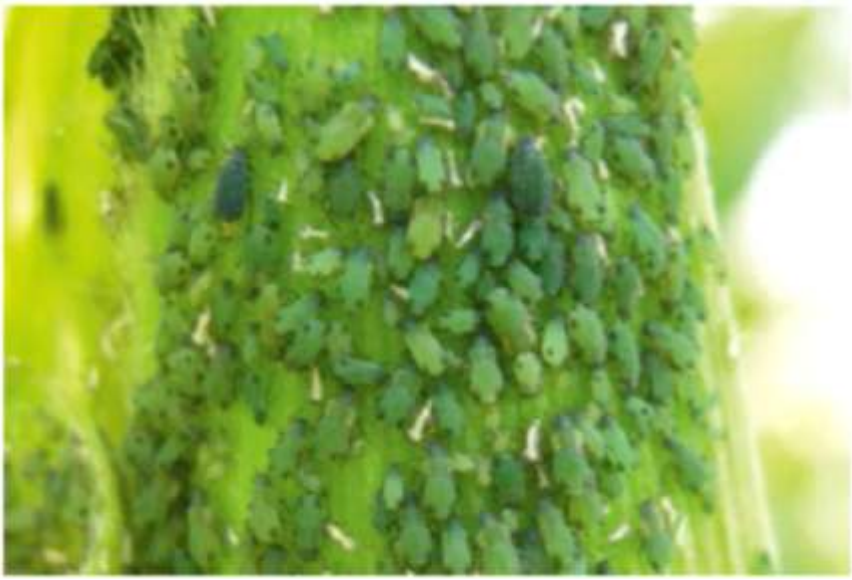

Figure 21: Aphids feeding on maize can spread Xanthomonas bacteria (Source: Johnnie Van den Berg, in VIB, 2017)

It should be noted that insect pests also function as carriers (vectors) of countless viral diseases, and the damage they cause enhances fungal and bacterial infections, thereby contaminating food with microbial toxins.

A prime example of the beneficial role of plant biotechnology is the development of GM insect-resistant (IR) crops that express insecticidal toxin genes from the soil bacterium, *Bacillus thuringiensis* (Bt). The bacterium is considered harmless to other

beneficial insects and mammals as the different strains release different toxins, which are highly specific against small taxonomic groups of insects (Sanahuja *et al*., 2011). In developing nations, GM IR crops have been extremely valuable in enhancing yields, reducing pesticide use and fuel required for spraying, and increasing farmers' income while simultaneously conserving biodiversity (Brookes and Barfoot, 2018). India's adoption of GM IR crops strongly supports the potential of plant biotechnology to contribute towards achieving SDGs 1 and 2. In 2016, over 7.5 million small-scale farmers in India cultivated a total of 10.42 million hectares (ha) of GM IR cotton, accounting for 96% of the total cultivable cotton area (Brookes and Barfoot, 2018). This has boosted farm income from GM IR cotton by US$21.12 billion over a 13-year period (2002 to 2016) and US$1.5 billion in 2016 alone. These enormous impacts have been enjoyed by these farmers and their families and have contributed immensely to the improvement of economic status in the community (ISAAA, 2017). For South Africa, only GM IR cotton was grown on 17,840 ha of land, with a cumulative farm income benefit of $34.5 million since 1998 (Brookes and Barfoot, 2018). Since 2000, GM IR maize has been cultivated on a commercial scale in South Africa. In 2016, 91% of maize produced (2.63 million ha) in South Africa were GM IR cultivars. The increase in farm income in 2016 was $293.6 million and cumulatively, $2.17 billion since 2000.

Interestingly, the use of GM IR technology prompted an overall increase in national maize production by 9.6% in 2016. However, for Nigeria, the first GM crop, the pod borer resistant (PBR) cowpea was just recently approved for environmental release on January 28, 2019 while awaiting the release of GM IR cotton.

The weed challenge

Weed management is the single largest input in agriculture globally. Agriculture in developing countries still depends on manual labour, mostly by women who spend several hours weeding (Akobundu, 1991). However, weed management in the developed world is highly mechanized, and has benefited immensely from the technological gains provided by broad-spectrum herbicides and GM herbicide-tolerant (HT) crops (Yuan *et al*., 2011).

Maize is the most-produced cereal worldwide. The crop forms the basis for food security in some of the world's poorest regions in Africa, Asia and Latin America (FAO, 2006). It is the most important cereal in SSA, where it contributes almost half of the proteins and calories consumed (VIB, 2017 http://www.vib.be/en/about-vib/Documents/VIB_MaizeInAfrica_EN_2017.pdf). About 24% of farmland in Africa are occupied by maize, which is more than any other staple crop. As a food crop, maize accounts for 73% and 64%

of the total demand in Southern and Eastern Africa, and Central Africa and Western, respectively (Shiferaw *et al*., 2011). However, one of the greatest challenges to maize farming in SSA is Striga, a parasitic flowering weed that attacks several crops, causing a reduction in grain yield due to stunted growth and withering of plant stands (Figure 22).

Figure 22: The parasitic weed Striga hermonthica in a maize field in Kenya (Source: Johnnie Van den Berg, in VIB, 2017).

An herbicide tolerant maize variety, StrigAway®, capable of selectively reducing Striga infestation in the field has been developed. However, the general consensus is for the development of a complementary biotechnology solution that will involve the introduction of Striga resistance directly into maize (Mbuvi *et al.,* 2017). GM HT maize has been commercially cultivated in South Africa since 2003. In 2016, out of a total planting of 2.6 million

hectares, GM HT maize cultivars were grown on 1.93 million hectares. A net farm income gain of $17.4 million was recorded in 2016, with a cumulative income gain of $65.2 million since 2003. A recent study on gender-aggregated benefits by Gouse *et al.* (2016) showed that female smallholder farmers value GM maize higher than their male counterparts owing to the labour-saving benefit the technology offers. I, therefore, strongly suggest that the development and adoption of GM IR/HT Maize be embraced by Nigerian stakeholders, considering the role the crop could play in addressing the food and feed deficit recently recorded in the country.

The drought challenge

Agriculture is extremely dependent on water, however, with scarcity of fresh water, the effect of drought on crops can be severe (Figure 23). The application of biotechnology to develop drought tolerant varieties that require less water is beginning to attract growing interests.

Figure 23: Drought in South Africa has an enormous effect on maize yields (Source: Johnnie Van den Berg, in VIB, 2017)

Three different international research collaboration initiatives have been launched to tackle the problem of drought in maize production in Africa. These are the Water Efficient Maize programme for Africa (WEMA) (www.wema.org), the Drought Tolerant Maize for Africa (DTMA) (http://dtma.cimmyt.org) and the Stress Tolerant Maize for Africa (STMA) (http://www.cimmyt.org/project-profile/stress-tolerant-maize-for-africa/). These projects are devoted to supplying a royalty-free drought-resistant maize varieties for humanitarian use by 2019 (http://www.vib.be/en/about-vib/Documents/VIB_MaizeInAfrica_EN_2017.pdf). It is anticipated that the drought tolerant varieties should provide an ancillary 12 million tons of maize under moderate drought conditions in Africa, which would provide food for more than 20 million people who would otherwise rely on food aid (Yuan *et al*., 2011).

Interestingly, my research activities covered two of the crops mentioned above with reference to Nigeria; cotton and cowpea, with the aim of subduing poverty and dominating hunger, thereby contributing to the achievement of SDGs 1 and 2. As a Graduate Research Fellow at IITA from 1998 to 2001, I jointly carried out a pioneering research on cowpea regeneration and transformation with IR genes. Our research efforts were able to achieve multiple shoots induction and regeneration from cotyledonary nodes and

epicotyls of cowpea, with the use of modified Murashige-Skoog medium (MS) (Murashige and Skoog, 1962) supplemented with 6-Benzylaminopurine (BAP) (Obembe *et al.,* 2000a). Two major approaches, *Agrobacterium*-mediated and electroporation methods, were deployed by our research team at IITA to genetically modify cowpea with *Bacillus thuringiensis* (Bt) genes (Machuka *et al.*, 2002; Obembe *et al.*, 2005; Obembe, 2008a). While I was on post-doctoral training in India, I developed great interest in cotton regeneration and genetic transformation based on my discovery of the immense benefits the Indians have had through the development, adoption and commercial production of GM cotton. My research activities included establishment of *in vitro* culture (Obembe *et al*., 2010) and generation of high-frequency multiple shoots formation from Indian elite cotton cultivars (Figure 24, Obembe *et al*., 2011a).

***Figure 24: Induction of multiple shoot in an Indian cotton cultivar, Jawahar Tapti* (Obembe et al., 2011a)**

My interest also made me to delve into developing *in vitro* protocol for somatic embryogenesis in cotton (Obembe *et al*., 2011b). Somatic embryos are embryos derived from the somatic cells of the plants, but which resemble the zygotic embryos that result from sexual fertilisation. Somatic embryogenesis occurs in nature as one of the evolutionary strategies for asexual embryogenesis, to overcome various environmental and genetic factors that prevent fertilisation (von Arnold *et al*., 2002). Hence, somatic embryogenesis may be defined as a process in which bipolar structures resembling zygotic embryos develop from somatic cell (non-zygotic) without vascular connection with the original tissue (von Arnold *et al*., 2002).

Chancellor Sir, it should not be surprising to note that my early introduction into plant biotechnology research has been for the genetic improvement of kola nut. My M.Sc. research project was successful in establishing sterilization protocol, as well as establishing *in vitro* culture and generating morphogenic responses from kola tissues, which include callus formation and shoot bud formation (Obembe *et al.*, 1999, Obembe, 2000b, Obembe, 2000c).

SDG 3 - Good health and Well-being

Guaranteeing healthy lives and promoting the well-being at all ages is critical to sustainable development, as a healthy economy

depends on a healthy people (Figure 25).

Figure 25: A family living in good health and wellbeing

The United Nations fact sheets reported that although significant progress has been made in increasing life expectancy, more than six million children under age five still die annually and an increasing proportion of such deaths (four out of every five) are in SSA and Southern Asia (http://www.un.org/sustainabledevelopment). This can be attributed partly to the prevailing challenge of widespread poverty in the two regions, as children born into poor families are almost twice more likely to die before the age of five than those born into wealthier families. Also, the deaths are mostly caused by preventable or

treatable diseases, and the mortality rate is worsened by poor maternal health, which is typically a manifestation of persistent acute malnutrition. It is also sad to note that the proportion of women who die from childbirth compared to those who survive in developing regions is still 14 times higher than in the developed regions. Furthermore, only half of women in developing regions receive the recommended level of health care they need (http://www.un.org/sustainabledevelopment), as such the regions account for 99% of the 830 daily global maternal mortality (Figure 26, http://www.who.int/news-room/fact-sheets/detail/maternal-mortality). Yet again, over half of these deaths are reported to occur in SSA.

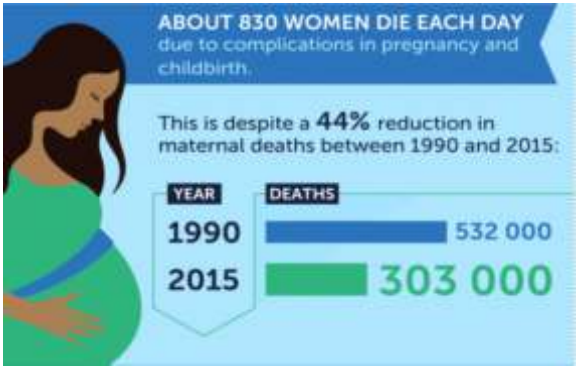

Figure 26: Global maternal mortality rate (Source: https://www.who.int/news-room/fact-sheets/detail/maternal-mortality***)***

SDG 3 seeks to achieve less than 70 maternal deaths per 100,000 live births and reduce premature deaths due to incommunicable diseases by one third by the year 2030.

The Role of Plant Biotechnology in Improving Food Nutritional Quality

Appropriate nutrition is crucial to effectively prevent diseases because undernourishment debilitates the immune system and increases vulnerability to diseases. Vitamin A, iron and zinc deficiencies have the most deleterious effect on child health. These deficiencies are also the commonest in developing countries, due to the fact that major crops such as white maize and rice are naturally lacking in these compounds (Freedman *et al.,* 2005). Various approaches have been advanced to address the micronutrient deficiencies. These include the use of mineral supplements, fortification of processed food, biofortification of food crops with mineral-rich fertilisers and the classical breeding to develop mineral-rich staple crops, and the use of plant biotechnology for nutritional improvement (Go´mez-Galera *et al.,* 2010). Among these strategies, only classical breeding and plant biotechnology provide germplasm as a sustainable resource, and only plant biotechnology allows the direct introduction of genes into local varieties (Yuan *et al.,* 2011).

Plant genetic engineering allows controlled and specific delivery of more efficient and novel genes while RNA-programmable CRISPR/Cas9 genome editing technology has great potential for snipping defected or unwanted genes for development of crop germplasm with high levels of nutrients (Doudna and Charpentier,

2014). For instance, engineered 'golden' rice that produces and accumulates β-carotene (pro-vitamin A) has the potential of dominating malnutrition in the impoverished developing world, especially in young children and lactating mothers (Figure 27, Ye *et al.,* 2000; Paine *et al.,* 2005). Vitamin A is essential for bright vision and normal functioning of the immune system. 127 million people including 25% of pre-school children suffer from Vitamin A deficiency (VAD) in developing countries. VAD was responsible for over half a million cases of permanent blindness in children and 2.2 million deaths annually (UNICEF, 2006). This is particularly so, in SSA and Southern Asia where VAD was 48% and 44%, respectively, in children aged 6-59 months old (ISAAA, 2017).

Figure 27: Golden Rice – rich in pro-vitamin A (Source: https://leganerd.com/wp-content/uploads/2016/07/cropped-golden-rice3.jpg)

One more vital micronutrient that is pertinent to achieving SDG 3 is folate. Whereas microorganisms and plants can synthesise

folate, mammals (including man) are unable to produce it. Hence, they depend on food sources, such as liver, eggs, green leafy- and leguminous vegetables. However, some staple foods such as white maize, wheat, rice and potatoes have little folate (Blancquaert *et al.,* 2010). Folate deficiency is a global health problem that occurs even in developed countries, it increases the risk of many diseases, including foetal neural tube defects (leading to miscarriages or complications during delivery), megaloblastic anemia, cardiovascular disease, and certain cancers (Nazki *et al.,* 2014; Herrera-Araujo, 2016). Pregnant women require at the minimum, 600 mg of folate per day, however, rice and maize do not provide sufficient amounts. Even though fortified foods or synthetic folic acid pills are used to alleviate folate deficiency in the developed world (Blancquaert *et al*., 2014), developing countries do not have folic acid supplementation programmes. Besides, excessive use of synthetic folic acid has generated much concern (Liang *et al*., 2019). To this end, two soybean genes, Gm8gGCHI and GmADCS driven by endosperm-specific promoters were co-expressed in maize and wheat, the two major staple crops, to boost their folate metabolic flux (Liang *et al*., 2019). The resulting transgenic corn and wheat endosperms were found to accumulate folate by 4.2-folds and 56.6 folds, respectively. Furthermore, tomato fruit with enhanced nutritional content (lycopene, amino acids, choline, organic acids and sugars) and extended shelf-life

was developed using ripening-specific expression of spermine and polyamines spermidine (Mehta *et al.,* 2002; Mattoo *et al.,* 2006). The enhanced lycopene levels in the engineered tomato was 2- to 3.5-fold, which far exceeded that achieved by classical breeding approaches (Mehta *et al.,* 2002).

Recently, my research focus has been on the deployment of plant biotechnology approaches to increase production and utilization of underutilized African indigenous vitamin A-rich leafy vegetables, as dietary modification, with a view to contributing towards improved nutrition and the attainment of the SDG 3. In 2014, *in silico* analysis that was conducted on compounds characterized from ethanolic extract of *Cucurbita pepo* (pumpkin, "elegede") indicated that the vegetable has phytochemicals that are responsible for the anti-inflammatory and anti-cancer property (Rotimi *et al.,* 2014). Consequently, my research team worked on the development of *in vitro* propagation of pumpkin. We were able to achieve multiple shoots formation and plant regeneration in indigenous Nigerian pumpkin (Obembe *et al.,* 2017a). The same approach and similar results were reported for another indigenous Nigerian vegetable, *Launaea taraxacifolia* (wild lettuce "Yanrin") (Figure 28, Obembe *et al.,* 2017b). We have also investigated tissue culture studies of *Solanecio biafrae* ("wòròwó") (Bello *et al.*, 2018a; 2018b). Then, we worked on the nutraceutical,

pharmacological and pharmacotherapeutic importance of three underutilized vegetable species, *Solanecio biafrae* (Bello *et al.,* 2018c), *Telferia occidentalis* (fluted pumpkin) (Aworunse *et al.,* 2018) and *Moringa oleifera* (under review). Earlier works on Moringa have been on the local knowledge, use pattern, geographical distribution, morphometric and molecular characterizations of its genetic diversity, which have provided vital information that has implications for breeding for useful traits for food and for medicine (Popoola and Obembe, 2013; Popoola *et al.,* 2014; Popoola *et al.,* 2016; Popoola *et al.,* 2017).

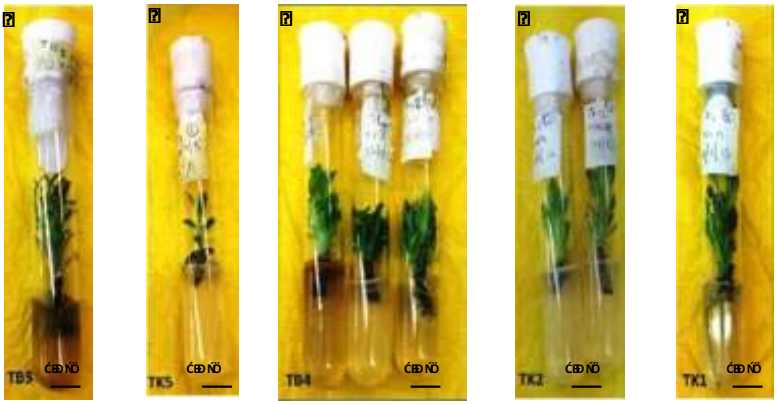

Figure 28: In vitro grown plants of L. taraxacifolia showing: (A.) Treatment with 2.5 mg/L BAP giving the highest number of shoots and leaves; (B.) Treatment with 2.5 mg/L kinetin forming single shoots; (C&D) Treatment with 2.0 mg/L BAP and kinetin giving higher shoot length than the control; (E.) treatment with 0.5 mg/L kinetin forming roots.

The Contribution of Plant Biotechnology to Affordable Pharmaceuticals

The key issues in pursuit of the SDG 3 are availability, accessibility and affordability of essential medicines and vaccines; ensuring that women have unlimited access to sexual and reproductive health care; and ending all preventable deaths of children (http://www.un.org/sustainabledevelopment). Molecular pharming, which is the application of plant biotechnology to manufacture pharmaceuticals was introduced in recognition that a significant impact could be accomplished on global access to health, as the technology holds potential benefits for the poor in the developing countries. The technology was particularly introduced to make for the challenge of low yield and poor-quality pharmaceuticals produced with the already existing living expression systems, such as the bacteria, yeast, insect and animal cells. As such, the use of plants as systems for the expression of recombinant proteins has been accepted as a cost-effective alternative approach for the production of cheaper and safer biopharmaceutical proteins. In 2010, I published a work in the African Journal of Biotechnology, which enumerated the comparative advantages of the plant-based systems over other established systems (Obembe, 2010). These advantages include low cost of production, very high scale-up capacity, high product quality, low contamination, easy storage and medium social

acceptance level. There are two main approaches to engineering plants as bio-factories to produce pharmaceutical products. These include using the plants as bioreactors (expression platforms) to bioaccumulate the biopharmaceuticals and then extracting and purifying the drugs afterwards, as in the case of using the chloroplast for high level expression of a microbicide protein (Oey *et al.,* 2009; Obembe *et al.,* 2010). The second approach is to use the plants as both expression platforms and delivery vehicles, as in the case of using plants to produce oral vaccine. Using the first approach, several plant-derived pharmaceuticals, including diverse vaccines, antibodies, therapeutic and nutraceutical proteins have been produced with successful clinical trials and commercialization. An overview of some of these life-saving plant recombinant proteins were published in the Journal of Biotechnology Advances as my additional contribution to the field of Molecular farming in 2011 (Obembe *et al*., 2011). Of particular relevance to the global goal of achieving affordable medicines and vaccines is the possibility of using the second approach to produce cheap oral vaccines in an edible plant organ, such as tubers, fruits or cereal seeds. These organs will then be administered as part processed food (e.g. puree or juice) that would be appropriate for the mass immunization of adults and children in developing countries. It is noteworthy that diarrheal diseases account for 1.3 million of deaths among young children, most of which occur in

the resource-limited countries (Global Burden of Diarrhoeal Diseases Collaborators, 2017). Indeed, diarrhea-associated diseases account for 25 % of the deaths in young children living in Africa and South East Asia (Sidoti *et al.,* 2015). As such the use of plant-derived oral vaccines to prevent the disease is the most relevant application of the technology in the context of SDG 3. Such oral vaccines targeted against diarrhea have been produced in rice, maize, potato and tomato (Obembe *et al.,* 2011). It is also envisaged that the delivery of edible vaccines against common diseases in school children in developing countries could be additional encouragement for parents to send their children to school (Yuan *et al.*, 2011).

The Specific Contribution of Insect Resistant-and Herbicide-Tolerant Crops to Better Health

Reduced pesticide use as a result of the introduction and adoption of insect-resistant and herbicide-tolerant crops has led to improved health and safety of farmers and farm workers. The adoption of insect-resistant biotech crops, for instance, significantly reduced insecticide use, and as such the health gains from the reduction of hazardous chemical sprays for bollworm control in the cotton fields will lead to general wellness and a more productive citizenry (ISAAA, 2017). It was reported that the cultivation of GM IR and HT cotton and rice has led to a decline in hospital visits in South

Africa as well as generally reduced health problems in Australia and India (Brookes and Barfoot, 2018). A study conducted at the Beijing Institute of Technology (Zhang *et al.,* 2016) revealed that adoption of biotech crops in China could improve the general well-being of Chinese farmers. The results indicated that cultivation of biotech crops would lead to the replacement of toxic non-glyphosate herbicides with glyphosate herbicide, which might benefit farmers' health in China and elsewhere (Crop Biotech Update, October 19, 2016). The report revealed that none of the examined health indicators was associated with glyphosate herbicide, while the use of non-glyphosate herbicides was found to induce renal dysfunction, inflammation, and severe nerve damage. This result also has positive implications for biotech crops.

SDG 4 – Quality Education

It is generally believed that education is the foundation for improving quality of life as well as the key that will enable the achievement of several other Sustainable Development Goals (SDGs). With quality education, people can break from the cycle of poverty, they can live healthier and sustainable lives, and in tolerance among other people, thereby contributing to more peaceful societies. As such, the SDG 4 seeks to ensure quality and all-encompassing education for all and promote lifelong learning. The United Nations' data show that 22% of the more than 265

million children currently out of school are of primary school age. More than half of these children reside in SSA, making it the region with the highest number of out-of-school children in the world. The implication of this is that, the region, which has a high proportion of young population, will have to provide basic education for 444 million children between the ages of 3 and 15 by 2030, which is almost 3 times the numbers enrolled today (http://www.un.org/sustainabledevelopment). Sadly again, Nigeria contributes the most to this global problem, a situation where one in every five of the world's out-of-school children lives in Nigeria (https://www.unicef.org/nigeria/education).

Also worthy of mention is the UN's data, which show that an estimated one-third of countries in the developing regions have not achieved gender parity with respect to primary education. In SSA, Western Asia and Oceania, girls still face hindrances to entering both primary and secondary school, which translates into limited opportunities in the labour market for young women and lack of access to skills (http://www.un.org/sustainabledevelopment).

The Contribution of Plant Biotechnology to Quality Education

Though plant biotechnology may not directly play a role in achieving SDG 4, it can indirectly contribute to it by reducing hunger and poverty and improving health, as discussed for SDGs

1-3. By increasing the wealth-generating opportunities of the resource poor farmers in the rural communities with the provision of better crops, they could afford to enrol their children in school, thereby increasing the percentage of school children. Furthermore, GM crops create more time and opportunity for women and children to attend school rather than being forced to work in farms to weed and spray pesticides (Gressel, 2009). A study by Subramaniam and Qaim (2010) reported that the overwhelming adoption of GM IR cotton in India contributed immensely to unprecedented increase in school enrolment by primary-age children (especially girls) between 2001 and 2010.

SDG 8 - Decent Work and Economic Growth

The goal here is to promote all-encompassing and sustainable economic growth, employment and decent work for all (http://www.un.org/sustainabledevelopment) (Figure 29). Even though a global unemployment rate of 5.6% was recorded in 2017, Nigeria's unemployment rate increased from 22.7% to 23.1% in 2018 (Figure 30). This has grave implication on the economic growth. For instance, the annual growth rate of the world's Gross Domestic Product per capital, which is projected to reach 7 % by 2030 is merely 1.8 % in Nigeria, presently (Figure 31). In addition, the problem of Boko Haram insurgency in Nigeria was borne out of extreme poverty propelled by overwhelming unemployment

rate (90 %) in the northeastern region.

Figure 29: Job creation and youth employment in Nigeria (Source: Dalberg, 2016, http://www.sdgfund.org/job-creation-and-youth-employment-nigeria)

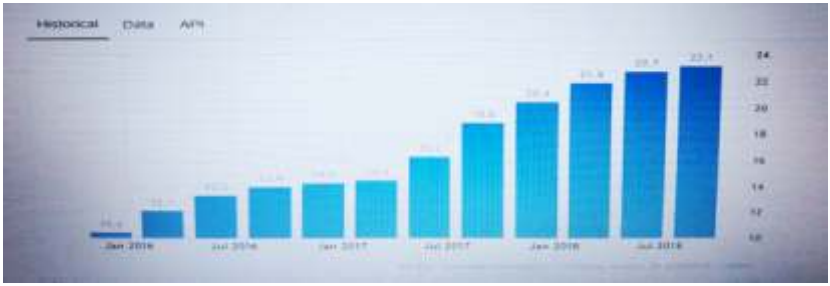

Figure 30: Unemployment rate in Nigeria (Source: Central Bank of Nigeria)

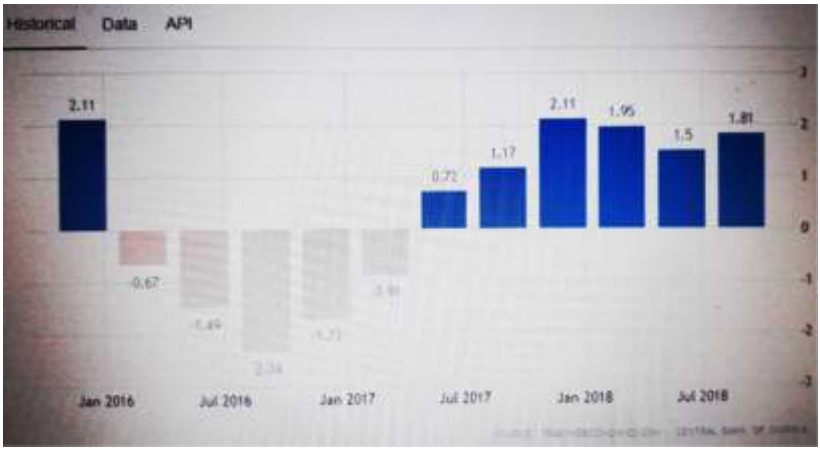

Figure 31: Nigeria's Gross Domestic Product per capital growth rate (Source: Central Bank of Nigeria)

The Society gains, when more people are productive and contribute to their country's growth. Poverty reduction can only be achieved through the creation of stable and well-paid jobs. Hence, to achieve sustainable economic growth, societies would need to create job opportunities and decent working conditions to stimulate the economy.

Contribution of Plant Biotechnology to Employment

Global energy security as well as the need for mitigating climate change have necessitated a shift towards alternative, renewable energy sources, especially bioenergy (IEA, 2007; 2015). Brazil is the second largest producer and important exporter of bioethanol

after USA. The Brazilian bioethanol programme has created about one million direct jobs (Koizumi, 2014). Furthermore, it is estimated that another one million job opportunities have been created in the sugarcane, sugar and bioethanol sectors as well as the transportation sector, the agricultural chemical sector and the agricultural machineries sector (Koizumi, 2014; Brinkman *et al*., 2018).

According to a study published by Trigo (2016) on the impacts of biotech crops (soybeans, maize and cotton) in Argentina over the 21 years of its commercialization (1996-2016), a gross benefit of US$126.97 billion was recorded and a total of about 2,052,922 jobs were created. A study by Brookes and Barfoot (2018) reported an increase in farm income from biotech soybean and maize in Uruguay by an estimated US$284 million from 2000 to 2016. These economic gains have also indirectly created over 40,000 well-paid jobs in the trade and industry sectors.

Kouser and Qaim (2017) reported detailed analyses of farm survey data collected on employment effects of GM IR (Bt) cotton adoption in Pakistan, using double-hurdle regression models and gender disaggregation. The analyses showed that adoption of Bt cotton has triggered a 55% increase in the demand for hired labour, and that the job-generating impacts are especially strong for women, who often belong to the most disadvantaged gender in rural societies. The results suggested that Bt technology can contribute to more equitable rural development and additional

employment income for the poor.

My specific contributions that are relevant to decent work creation, using plant biotechnology are in two diverse areas: (1) *in planta* modification of cell wall for enhancing cellulose fibre properties and (2) molecular farming for producing plant-derived pharmaceuticals and non-pharmaceuticals.

In planta modification of cell wall for enhancing cellulose fibre properties

The possibilities of dominating over plant cell wall cellulose fibre characteristics with a view to tailoring them for specific industrial applications were published in our paper, Obembe *et al.* (2006). Plant cell wall polysaccharides are the predominant components of fibres. Natural fibre is a thread-like material from plants (Figure 32), which have a wide range of industrial applications (Obembe *et al.,* 2006). Wood fibres from tree species have found application in pulp and paper industries whereas cotton, flax, jute, hemp and agave fibres are used in the textile

Figure 32: Jute fibre, one of the most widely used fibre (http://www.yarnsandfibers.com/news/textile-news/)

The goal of our research was to engineer the plants for in planta modification of cellulose biosynthesis and the interactions of cellulose with non-cellulosic polysaccharides for various industrial applications, such as the production of cellulose fibre with high tensile strength for textile manufacturing and the production of fibres with less attachment of lignin for paper manufacturing. This was with a view to developing a cheaper alternative to chemical derivatization or in vitro enzyme-mediated modification of fibres for tailoring cellulose fibres with enhanced properties for specific industrial applications. Furthermore, due to environmental considerations, the demand for natural fibres as alternative composites to synthetic polymers in domestic sector, building and construction, electrical and electronics (circuit boards), automotive (Figure 33) and aircraft industries is also increasing (Obembe et al., 2006). In fact, more than 200 commercial, civil and military aircraft components (Figure 34) are currently being manufactured through biocomposite materials worldwide (Saba et al., 2017).

The global biocomposites market size was estimated at USD 15.99 billion in 2016 and is expected to grow to USD 46.3 billion by 2025 (Grand View Research Report May 2018, https://www.grandviewresearch.com/press-release/global-biocomposites-market).

Figure 33: The hemp biocomposite electric car – Canada's first biocomposite electric car (https://newatlas.com/kestrel-ev-pictures-released/16380/)

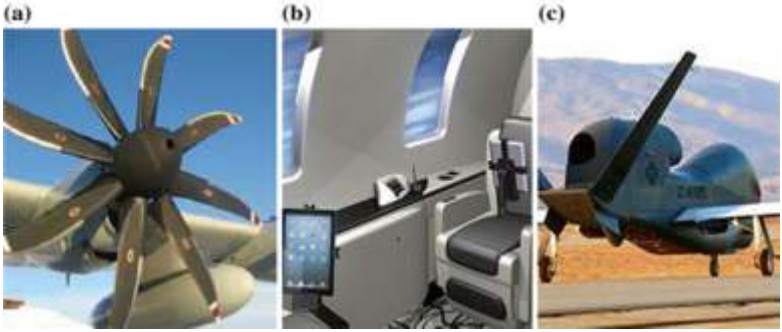

Figure 34: The propeller systems: (a), cabin equipment (b) and wheels/ brakes of the aircraft (c) made from biocomposite (Source: Saba et al., 2017)

We later attempted to demonstrate our concept by using carbohydrate binding modules (CBMs) of a cell wall loosening protein (expansin) and cell wall degrading enzymes to achieve modulation of cell wall architecture. The investigation with the CBM of a putative potato expansin (EXPA) targeted to the cell walls of tobacco plants demonstrated that expansin CBM alone (not necessarily the full-length protein) can bring about changes in the plant cell walls, as the transgenic stems exhibited enlarged xylem cells and thin cell walls (Figure 35, Obembe *et al.,* 2007a).

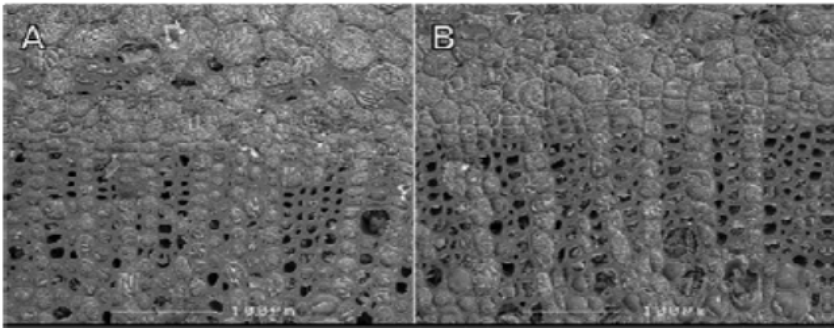

Figure 35: Scanning electron micrographs (SEM) of stem vascular tissue of non-transformed tobacco plant (A) and a transgenic tobacco line (B), at x300 magnification.

We then investigated heterologous expression of two types of carbohydrate binding module (CBM) in tobacco cell walls. These are the promiscuous CBM29 modules (a tandem CBM29-1-2 and its single derivative CBM29-2), derived from a non-catalytic protein1, NCP1, of the Piromyces equi cellulase/hemicellulase

complex, and the less promiscuous tandem CBM2b-1-2 from the Cellulomonas fimi xylanase 11A. The promiscuous CBM29-1-2 had much more pronounced effects on transgenic tobacco plants than the less promiscuous CBM2b-1-2. Reduced stem elongation and prolonged juvenility, resulting in delayed flower development, were observed in transformants expressing CBM29-1-2 whereas such growth phenotypes were not observed for CBM2b-1-2 plants (Figure 36, Obembe *et al.,* 2007b).

Figure 36: Reduced stem elongation and prolonged juvenility of CBM 29-1-2 transgenic tobacco plants after week eight.

Histological examination and electron microscopy revealed layers of collapsed cortical cells in the stems of CBM29-1-2

plants whereas cellular distortion in the stem cortical cells of CBM2b-1-2 transformants was less severe (Figure 37, Obembe *et al.,* 2007b). Whereas altered stem expansion was noticed in only xylem cells of CBM2b-1-2 stems, most parts of the CBM29-1-2 stem exhibited altered cell expansion and thinner cell walls (Figure 38).

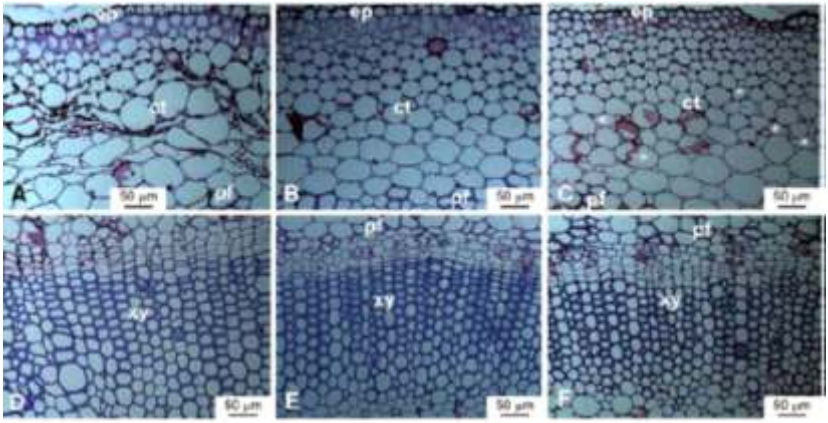

Figure 37: Micrographs of x10 magnification of cross sections of CBM29-1-2 stem showing enlarged cortical cells and xylem tissues (a, d), non-transformed control stem (b, e), and irregularly shaped cortical cells of the CBM2b-1-2 stem (c, f). ep epidermis, ct cortex, xy xylem, pf phloem fibre

In order to provide evidence that all the morphological, developmental and anatomical manifestations we observed in our results were the consequences of CBM genes we have transformed into the tobacco plants, we carried out immunolabelling detection

of the CBMs binding to stem of the non-transformed tobacco plant. This was to determine the particular tissue of the stem that the CBMs would bind to in the wild-type tobacco plant. The result revealed that CBM29-1-2 bound indiscriminately to all the tissues of the stem while CBM2b-1-2 binding was restricted to the vascular tissues (Figure 39). This result lends credence to the more pronounced effects of the CBM29-1-2 than CBM2b-1-2 that were observed in the transgenic plants. These results also gave additional support to the hypothesis that CBMs alone can modify cell wall structure leading to modulation of wall loosening and plant growth (Obembe *et al*., 2007b).

In a separate investigation, the expression of a CBM22-2 from *Clostridium thermocellum* xylanase in transgenic tobacco plants was evaluated. We reported that the family 22 CBM is not a potential candidate for use in *in planta* modification of the cell wall (Obembe, 2008b).

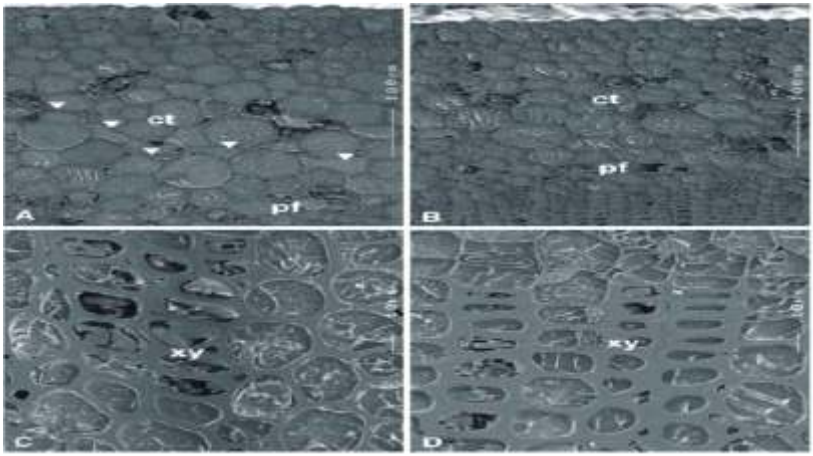

Figure 38: SEMs of transgenic tobacco stems showing bigger cells and thinner cell walls of the CBM 29-1-2 stems compared with non-transgenic control. CBM29-1-2 (a) and (c), and control (b) and (d). a and b show the cortex tissue whereas c and d show the xylem tissue. pf phloem fibre, xy xylem, ct cortex. Arrow heads show malformed cortical cell layers

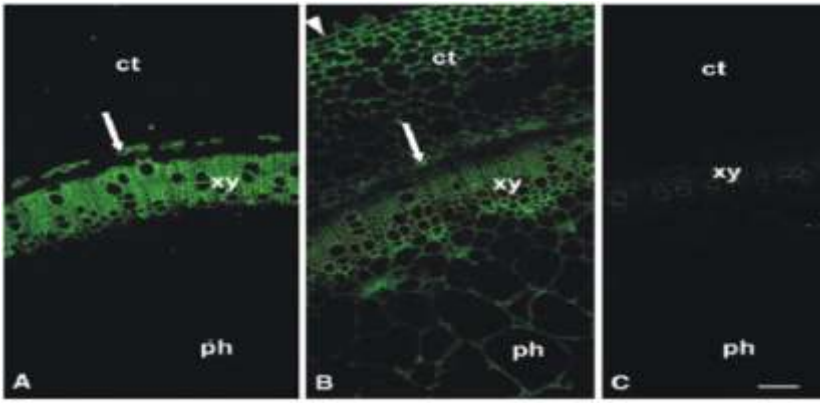

Figure 39: Immunofluorescence micrographs showing binding of CBM2b-1-2 (a), CBM29-1-2 (b), and control (no CBM) (c) to transverse sections of wild-type tobacco stem.

Next, we delved into modulation of cellulose biosynthesis in potato with a view to achieving modified cell wall architecture. We genetically crossed two transgenic potato lines csr2-1 and csr4-8, containing two different antisense constructs, csr2 and csr4 and whose tuber cell walls exhibited low levels of cellulose as compared to the control. The aim was to investigate the possibility of achieving further reduction in cellulose content in the tuber cell walls of the progeny and to determine the phenotypic and developmental implications of the reduction. Cellulose synthesising enzymes are conceived to exist as complex of many enzymes. It was hypothesized that the changes would be more pronounced in the progeny, should the two CesA enzymes, whose genes have been down-regulated with the antisense constructs be members of the same cellulose synthase complex. We reported the expected segregation ratio of 1:1:1:1 of the four classes of the transgenes as well as whole plant phenotype characterization, which indicated combined effects of the two transgenes on tuber production in the progeny with the production of smaller tubers, plausibly due to reduced cellulose content in the cell walls (Figure 40, Obembe *et al.,* 2008).

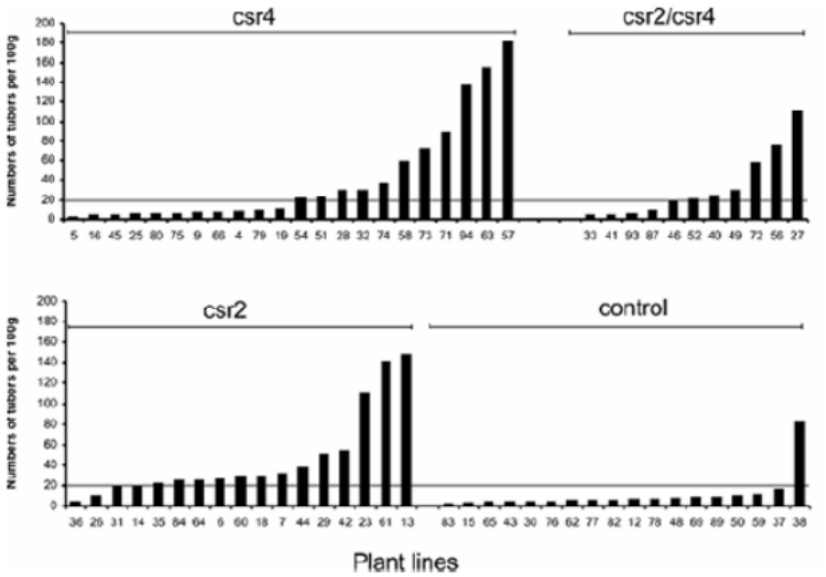

Figure 40: Number of tubers of progeny corresponding to normalized 100 g weight. Average weight of tuber for a particular F1 plant is deduced by dividing the normalized 100 g weight by the corresponding number of tubers.

Histochemical staining and microscopic examinations of the progeny tubers were made to investigate cellular phenotype in the tubers. We observed remarkable proliferation of xylem cells and abnormal lignin formation in the progeny containing single csr2 construct (Figure 41). Hence, the results provided evidence of cellular phenotype due to the presence of the antisense construct (Obembe and Vincken, 2008).

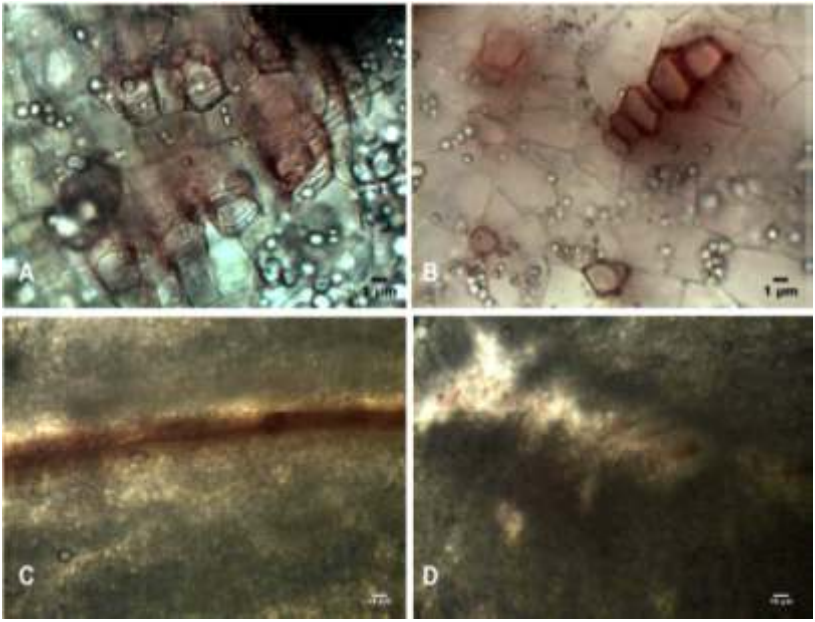

Figure 41: Phloroglucinol staining and micrographs of fresh potato tuber sections (A), showing ectopic xylem formation, (B) the control, showing normal xylem, (C) showing the vascular rings of csr2 tubers in perpendicular orientation to the stolon axis and xylem (red dots) in the control in normal, parallel orientation to the stolon axis (D).

Additionally, fluorescence microscopy with calcofluor white was used to investigate the effects of the two antisense constructs in the same genetic background, with respect to cellulose deposition in the potato tuber cell walls of the progeny. It was remarkable to observe that fluorescence was intense in the cell corners and less intense and uneven fluorescence around the cells of the csr2 tubers as compared to others (Figure 42).

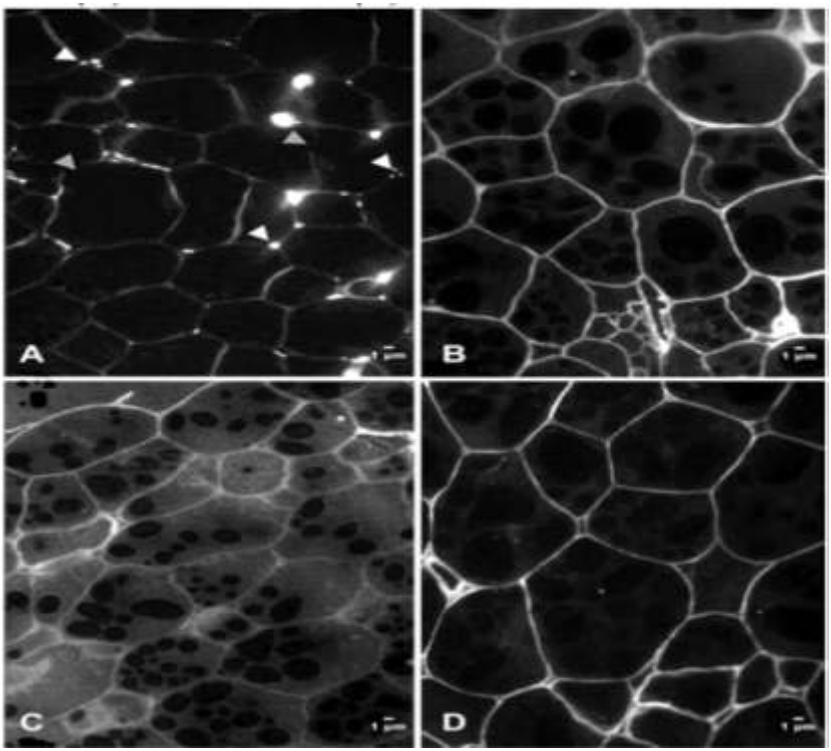

Figure 42: Calcofluor white staining of potato tuber sections. Fluorescence micrographs of tissues of (A) csr2, (B) csr4, (C) csr2/csr4 and (D) the control tubers.

Even though the study indicated that the defect of a primary cell wall synthesising enzyme complex (CesA) as a result of the combined antisense constructs could have significant influence on cellulose deposition, and consequently cell wall architecture (Obembe, 2009), this speculation was found to be true only for

cellulose deposition, as there was no evidence of defective cellulose synthase (CesA) complexes (Figure 43, Obembe, 2010).

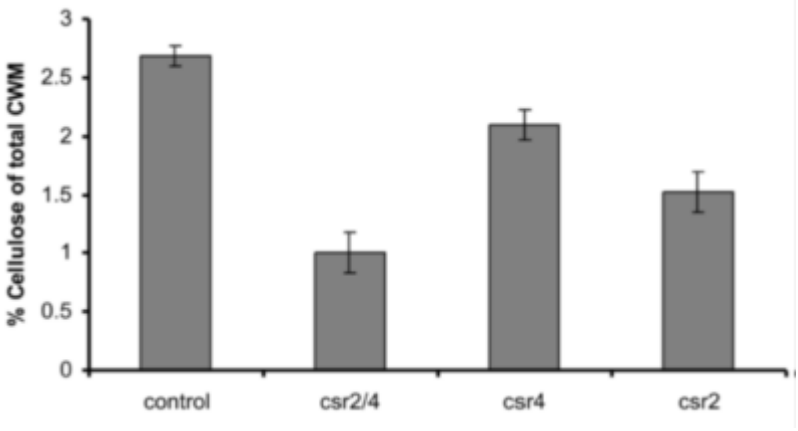

Figure 43: Cellulose content in the offspring tubers. The cellulose levels are represented as the percentage of cellulose in total cell wall material.

However, we finally investigated transcript expression profiling of the CesA gene transcripts in the wild type and in the offspring derived from the genetic crossing of the two antisense potato lines using Quantitative RT-PCR, which showed differential CesA gene expression patterns. In most tissues, particularly in the tuber, CesA2 mRNA was found to be relatively more abundant than CesA4 mRNA (Figures 44a and 44b). We were able to show that the proteins of the potato CesA2 and CesA4 genes were not present in the same enzyme complex (Obembe *et al*., 2009).

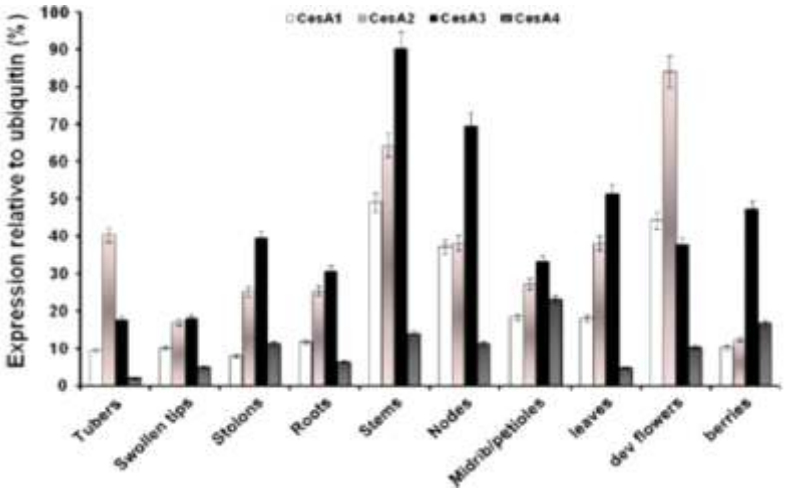

Figure 44a: Quantitative RT-PCR analysis of CesA genes in various tissues of the wild-type potato. RNA levels for each were expressed relative to the amount of ubiquitin RNA and multiplied by 100.

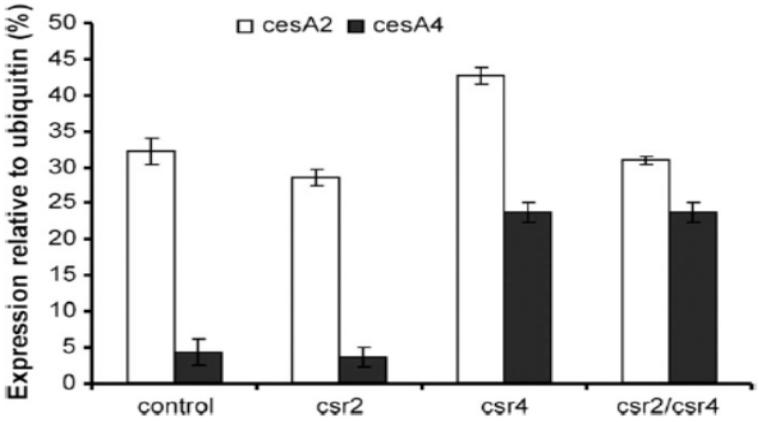

Figure 44b: Quantitative RT-PCR analysis of CesA2 and CesA4 genes in the tubers of the offspring

Cellulose fibre research is not limited to the afore-mentioned industrial applications, it also has application in the energy sector. The skills set for modification of cell wall architecture could be applied to energy crops as well, these are the grasses (rice, maize, wheat, sorghum and millet), which have high biomass (straw/stalk) production. The concerns about food security are the incentive for the present focus on the lignocellulose residues of these energy crops as alternative to sugar-based bioethanol production. Hence, their plant cell walls can be genetically modified for efficient biomass degradation and conversion with promising positive impacts on job creation.

Molecular farming for producing plant-derived pharmaceuticals and non-pharmaceuticals

It is noteworthy that employment needs in the industry are growing at a fast pace. In the U.S. alone, the TEConomy 2016 Report stated that "the Bioscience Industry employed 1.66 million in 2014 across more than 77,000 U.S. business establishments", adding "an additional 7.53 million jobs" (TEConomy, 2016). Even in Europe, the Lisbon European Council launched the Lisbon Strategy in March 2000 with the aim of making the European Union the world's most competitive and dynamic knowledge-based economy capable of sustaining economic growth, with more and better jobs and greater cohesion

(Presidency Conclusion, 2000). Biotechnology was one of the new technologies for the Lisbon Strategy (Presidency Conclusion, 2001).

The market value of biopharmaceuticals alone hit $188 billion in 2017 and is still increasing (http://www.lamerie.com; Walsh, 2018). Interestingly, 40% of the 6,000 or more products presently in clinical stage of development worldwide are biopharmaceuticals. It has been projected that plant-derived drugs as a segment will grow from $29.3 billion in 2017 to about $39.2 billion by 2022 with a 5.9% compound annual growth rate for the 2017-2022 period (https://www.reportlinker.com/p0118047).

My contribution to plant molecular farming was published as a research review article (Obembe *et al.*, 2011) and it is my most cited paper. The paper highlighted the various cost-effective technologies and strategies, which are used to improve yield and quality of the plant-derived pharmaceuticals, in order to make plant-based production system suitable alternatives to the already established systems. It also gave an overview of the different novel plant-derived pharmaceuticals and non-pharmaceutical protein products that were at various stages of clinical development or commercialization. Lastly, it discussed the biosafety and regulatory issues.

It is envisioned that the development of institutional, national and regional capacities in plant molecular farming would contribute to

the overall development goals of the region. These include the creation of niche markets for these novel products, thereby contributing to decent job creation, inclusive and sustainable economic growth, and ultimately enhanced industrialization.

RECOMMENDATION

Almost 10 years after, my paper entitled "The Plant Biotechnology Flight: Is Africa on board" is still very relevant in the context of capacity building because there has not been much change since then. The various stakeholders in the region should have strong will to drive this through, even in the presence of unfounded negative sentiments against genetic modification from some quarters. The impacts of plant biotechnology in some emerging economies in Asia and Latin America are glaring for all, and as such the strategies adopted by these countries are worth replicating here also. In the light of the foregoing, my modest recommendation in achieving improved plant biotechnology development and adoption in Africa would be in the area of awareness campaigns about the new technology, particularly as it concerns the potential benefits and to reduce public fear over its safety. There is also need for curriculum development, starting from the secondary school level, as man power development for biotechnology should be based on long term trainings rather than through seminars and workshop. Besides, basic infrastructures

such as plant tissue culture and molecular biology laboratories should be made available for the universities and research institutes. Research activities of researchers in these establishments should be funded as well. In addition to equipping and funding the universities and research institutes, the specialized Biotechnology Centres and Agencies in Nigeria, such as the National Centre for Genetic Research and Biotechnology (NACGRAB), National Biotechnology Development Agency (NABDA), and Sheda Science and Technology Complex (SHESTCO) should be adequately funded. It should be noted that none of the above interventions would make any meaningful impact if there is no steady power supply, broadband internet connectivity and portable water. Furthermore, the Nigerian investment climate should be made more conducive to attract foreign investments, as the biotechnology industry in the US has been consistently successful over three decades now. Finally, the National Biosafety Management Agency (NBMA) should be empowered to enforce its guidelines and to establish state-of-the-art certification and testing facilities.

CONCLUDING REMARKS

The Chancellor, Sir, distinguished ladies and gentlemen, the development and adoption of plant biotechnologies and products in African countries, including Nigeria would go a long way in

contributing to the achievement of the five SDGs under consideration. It is envisioned that the availability of improved GM seeds with stacked traits of insect resistance and herbicide tolerance would improve African agricultural productivity tremendously thereby increasing the net farm income gain in multiple folds. Klumper and Qaim (2014) in their meta-analysis of 147 published biotech crop researches globally, in the last 20 years, arrived at the conclusion that there was 37% reduction in pesticide use, 22% increase in yield and 68% increase in farmers' income (Figure 45).

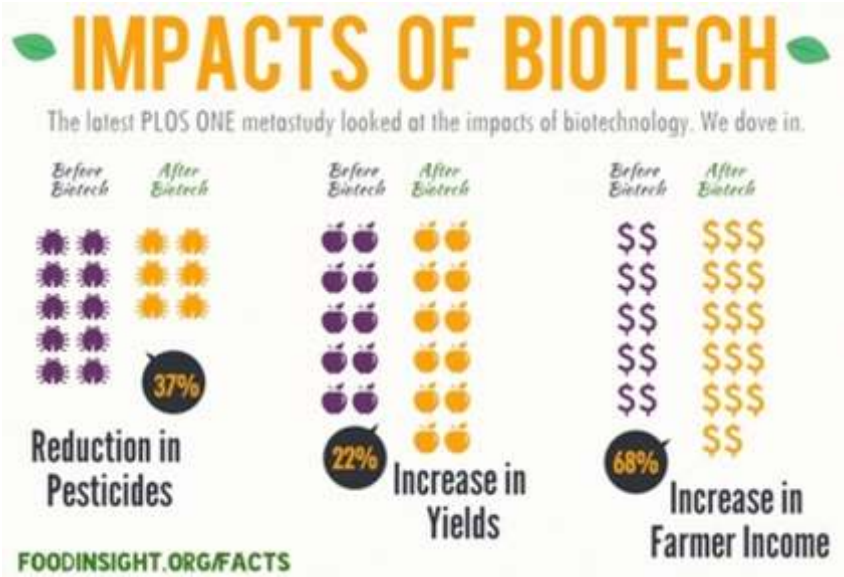

Figure 45: A meta-analysis on published biotech crop studies globally (Source: Klumper and Qaim, 2014)

It is also interesting to note that 24 countries have adopted commercial cultivation of biotech crops between 1996 and 2017, and six of these countries have gained tremendous economic benefits from the crops. These include the USA (US$80.3 billion), Argentina (US$23.7 billion), India (US$21.1 billion, Brazil (US$19.8 billion), China (US$19.6 billion), Canada (US$8 billion), and others (US$13.6 billion) for a total of US$186.1 billion (ISAAA, 2017; Brookes and Barfoot, 2018). It is noteworthy that the global economic gains in 2016 totalling US$18.2 billion were shared between the developing countries (US$10 billion) and industrial countries at US$8.2 (ISAAA, 2017; Brookes and Barfoot, 2018). This was largely because 19 of the 24 biotech crop-adopting countries are developing countries but disappointedly, only 2 of the 19 countries are African, South Africa and Sudan (Figure 46).

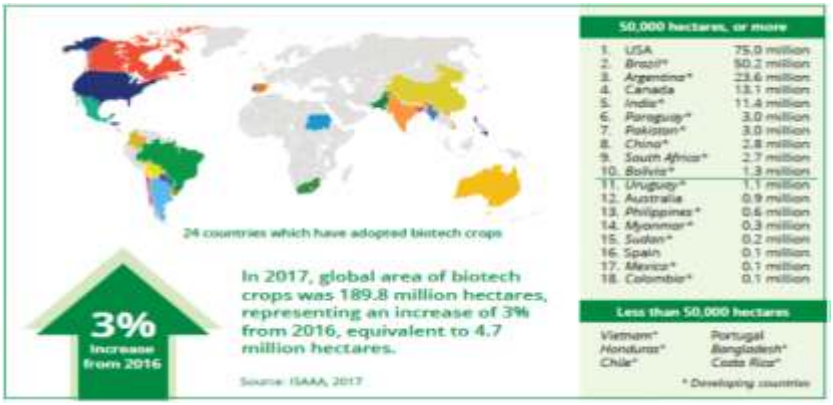

Figure 46: Global Area of Biotech crops in 2017 (ISAAA, 2017)

The trend nowadays is to stack at least two traits in one crop. Examples of such stacked-traited seeds are IR and HT maize and soybean, which have been making even greater impacts in terms of yields and income, thereby contributing immensely to poverty reduction (SDG 1) in the communities that have embraced the technology. Chancellor Sir, the problem of food insecurity in the SSA is not solely because there is insufficient food production but largely because of the pervading poverty. Hence, with improved prosperity of the resource poor people especially in the rural communities, there will be enough money to provide food for the family, thereby reducing hunger and malnutrition (SDG 2). Also, with improved farmer income, rural and urban farmers will be able to afford health care services for all, including women and children, which would engender good health and general wellbeing (SDG 3). Additionally, improved income would encourage farmers to send their children to school, leading to increased access to education, especially for the girl child (SDG 4). Moreover, apart from the recent novel application of plant biotechnology to engineer plants to manufacture recombinant products (pharmaceutical and non-pharmaceutical), leading to new form of industry and markets and creating new employment to trained personnel, improved agricultural productivity also would lead to increase in the demand for paid labour, especially women, thereby creating new jobs for the rural women (SDG 8).

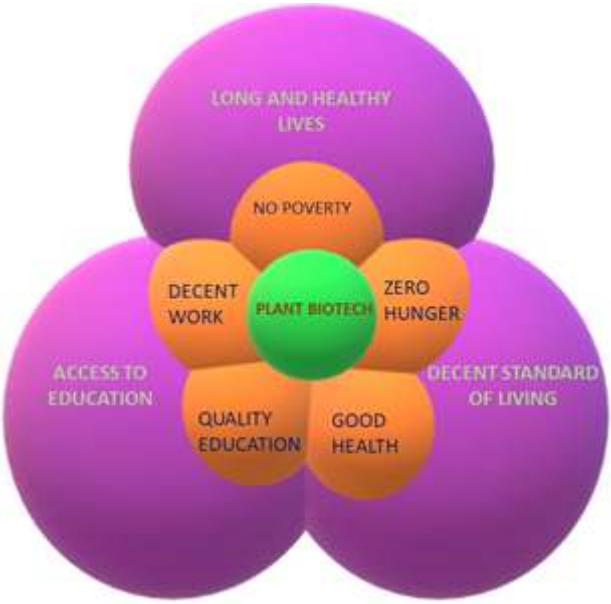

Figure 47: Summary of the inaugural lecture: positive impacts of plant biotechnology on the five SDGs will strengthen the three human development capabilities (foundations)

Hence, the positive impacts of plant biotechnology on these five SDGs, under consideration in this lecture will translate directly to the achievement of the three human development capabilities: (1) leading long and healthy lives, (2) having access to education, and (3) achieving decent standard of living (Figure 47, above). Indeed, any investment in plant biotechnology is an investment in achieving these five SDGs, and consequently an investment in

achieving the three human development capabilities.

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Dear esteemed audience, this lecture will not be complete if I do not testify to the mighty and sustaining hands of God over me over the years. Between 1993 and 1994, while I was rounding off my MSc. programme at Ife, I could have been blind or suffered brain damage, but God kindly spared my body from disability. I could have been paralysed from waist down during my early days here at CU (2007-2009) but God intervened and graciously opened a postdoctoral position for me in India, where I got the medical breakthrough I needed, just at the nick of time. In March 2012, I could have been dead through an auto crash when the devil was really mad at me and decided to strike hard. In the same week, he broke the arm of Nifemi (my son), broke the hip of Seyi (my associate's son), threw our 3,000 litre-overhead water storage tank on our house and damaged it, utterly destroyed my fence (front and

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This is my story! This is my inaugural lecture! Thank you all for your time.

Bi gbogbo irun ori mi je kiki ahon (2x)

Koto koto lati yin baba logo (2x)

Koto oo

God bless you all!

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