Chapter

Crop Biotechnology and Smallholder Farmers in Africa

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Abstract

The tools of genetic engineering and modern biotechnology offer great potential to enhance agricultural productivity, food and nutritional security, and livelihoods of millions of smallholder farmers in Africa. Large and long-term investments have been made in several countries in Africa to access, develop, and commercialize safe biotechnology crops derived through modern biotechnology. This chapter presents case studies of biotechnology applications and progresses achieved in six countries in Sub-Saharan Africa including Burkina Faso, Ethiopia, Kenya, Malawi, Nigeria, Sudan, and Uganda targeting to address biotic and abiotic constraints faced by smallholder farmers and malnutrition. Based on the past 20 years of experience, the chapter identifies constraints, challenges, and opportunities for taking safe biotechnology crops to smallholder farmers in Africa.

Keywords: biotechnology, biosafety, genetic engineering, GMOs, Burkina Faso, Ethiopia, Kenya, Malawi, Nigeria, Sudan, Uganda

1. Introduction

1.1 Smallholders' agricultural production and productivity in Africa

In Africa, smallholder agriculture is predominant and agricultural growth and poverty reduction are subjects closely associated with growth in smallholder agriculture for some time to come. An estimated 41 million smallholders [1] are the major source of food for nearly all rural and most urban dwellers in Africa. In Sub-Saharan Africa (SSA), most smallholders own less than two hectares holding of cultivable land and are challenged by the low productivity and production constraints in the middle of the unprecedented rising need for more food, feed, and raw material for industry. The SSA region alone has a quarter of the world's arable land endowment but produces only 10% of world agricultural output [2]. Unlike smallholders in Asia who dominantly grow few crops such as rice and wheat, African farmers experience diverse farming systems and grow very diverse crops that include maize (*Zea mays*), sorghum (*Sorghum* sp) millet (*Penisetum* sp), wheat (*Triticum aestivum*), and rice (*Oryza sativa*); pulses such as soybean (*Glycine max*), cowpea (*Vigna unguiculata*), beans (*Phaseolus* sp.), groundnut (*Arachis hypogaea*), and other crops such as cassava (*Matnihot esculentus*), sweet potato (*Ipomoea*

Farming systems	% of region		Principal livelihoods*
	Land area	Agric. population	
Irrigated	1	2	Rice, cotton, vegetables, rain-fed crops, cattle, poultry
Tree Crop	3	6	Cocoa, coffee, oil palm, rubber, yams, maize
Forest-Based	11	7	Cassava, maize, beans, cocoyams
Rice-Tree Crop	1	2	Rice, banana, coffee, maize, cassava, legumes, livestock, off-farm work
Highland Perennial	1	8	Banana, plantain, enset, coffee, cassava, sweet potato, beans, cereals
Highland Temperate Mixed	2	7	Wheat barley, tef, peas, lentils, broad beans, rape, potatoes,
Root Crop	11	11	Yams, cassava, legumes, off-farm work
Cereal-Root Crop Mixed	13	16	Maize, sorghum, millet, cassava, yams, legumes, cattle
Maize Mixed	10	15	Maize, tobacco, cotton, cattle, goats, poultry,
Agro-Pastoral Millet/Sorghum	8	8	Sorghum, pearl millet, pulses. Sesame and livestock
Sparse (Arid)	17	1	Irrigated maize, vegetables, date palms, cattle

**Source: FAO and World Bank, Rome and Washington DC 2006. (Adapted to show more crop-based farming system).*

Table 1.
Major farming systems of sub-Saharan Africa.

batatas), potato, (*Solanum tuberosum*), yam (*Dioscorea* sp), banana (*Musa* sp), cotton (*Gossypum* sp), and sugarcane (*Saccahrum officinarum*) (**Table 1**) [3].

Crop productivity in Africa specifically in the SSA region is below the world average (**Figure 1**) and the region constitutes the highest number of food-insecure population (35.5% of its population) of whom 21.3% are severely insecure [4] rendering the region increasingly dependent on imported food. Due to this and

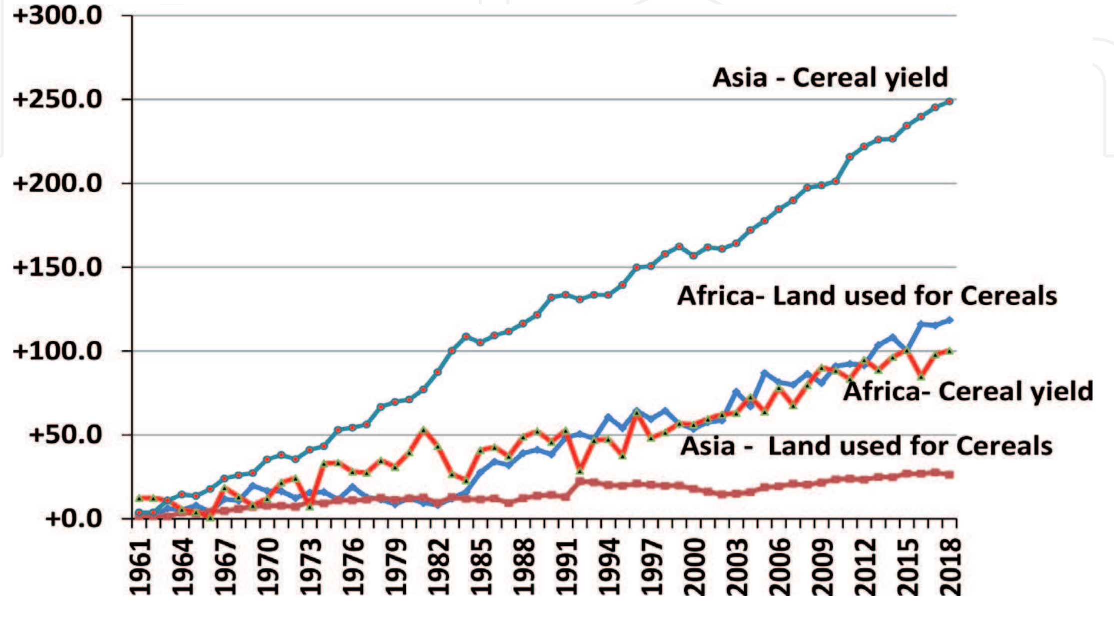

Figure 1.
Change (percent increase) of cereal yield and land used for cereal production. (Data source: Computed from Food and Agriculture Organization (FAO) of the United Nations. 2019 Report).

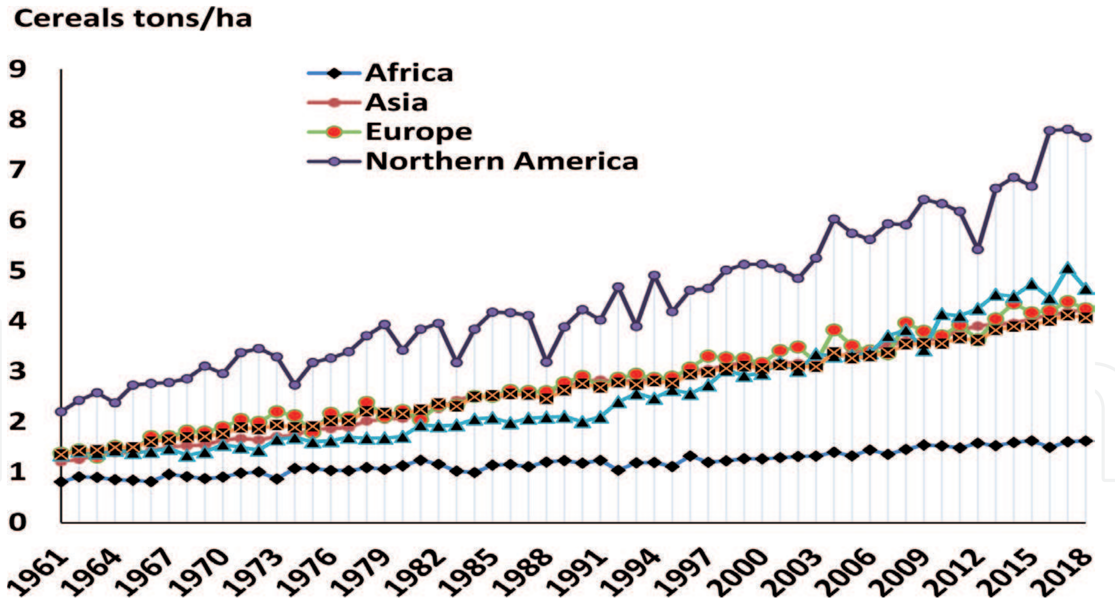

Figure 2.
Yield (t/ha) trends of cereal production in different regions of the world. (Data Source: Food and Agriculture Organization of the United Nations. 2019 Report).

other factors about 39 countries of the SSA account for the largest number of food-insecure people: 424.5 million (40.5% of the region's population) in the year 2020 [5]. It can also be seen that during the period 1961–2018, cereal yield in Africa has grown only one fold compared to a 2.5 fold increase in Asia, which had only 26.3% area increase compared to Africa with 1.2 fold increase (**Figure 1**). Therefore, whatever growth there has been in cereal production in Africa, it was largely due to land expansion in contrast to Asia. Food insecurity is forecasted to worsen due to climate change impacts and recurrent drought unless proper and quick measures are implemented [6]. The region will have a shortfall of nearly 90 million metric tons of cereals by the year 2025 if current agricultural practices remain unchanged. Productivity trends do not promise a better future for cereals and roots and tuber crops as can be seen from cereal performance during the period 1961–2018 average yield based on FAOSTAT data 2020 (**Figure 2**).

However, more factors are known to involve in constraining smallholder farmers' crops production and cause yield gaps. Low crop productivity is often related to biotic stresses such as those caused by insect pests, diseases, and weeds as well as the inherent low-yielding potential of varieties, and abiotic stresses caused by soil-related and climatic problems such as moisture stress and drought. The latter is a pronounced problem of vast marginal and drier agriculture areas of SSA. Crops grown in such marginal environments are exposed to frequent severe growing conditions. Each factor is responsible for substantial yield losses annually by smallholder farming. Furthermore, yield gains associated with high-yielding varieties if found much lower in SSA partly due to inadequate inputs, poor infrastructure, and market outlet including weak extension services. Thus, poor availability of improved technology packages (improved seeds, irrigation, fertilizers, and pesticides) makes it hard for millions of smallholder farmers to produce surplus and escape the subsistence type of life.

Successful mitigation of these biotic and abiotic constraints and institutional limitations affecting agricultural growth is a task that not only requires political will and sustained commitment by country governments in Africa, but also a stronger global collaborative effort to realize enhanced applications of modern technologies to complement and transform the conventional interventions efforts underway. Increased investments in agricultural R&D and fast-tracking the use of innovative technologies such as conventional as well as modern biotechnology and proven useful readily available biotechnology products is extremely needed to solve smallholder farmers' crop productivity problems. As such agricultural biotechnology offers enormous opportunities through innovative ideas, techniques, and processes to drive innovative solutions highly relevant for the needs of smallholder farmers in Africa [7]. Medium to long-term benefits of using advanced techniques of biotechnology that include tissue culture, micropropagation, gene, and marker discovery, genomics, genetic engineering, genome-editing, bioinformatics, and others through enhancing crop breeding including indigenous crop species cannot be overemphasized [8]. This chapter focuses on the deployment of modern biotechnology such as genetic engineering tools and products as well as challenges facing adopting countries in developing Africa. It also presents case studies of agricultural biotechnology uses and progresses in six countries in SSA focusing on the use of safe biotechnology crops to solve key biotic and abiotic constraints faced by smallholder farmers in the respective countries.

1.2 Promises of biotechnology to smallholder farmers

The rapid advancements in the field of biotechnology offer promising alternatives to the approaches of crop improvement. Biotechnology complements and makes the conventional breeding efforts in crops efficient through precise identification and introgression of genes in a much shorter time period. The integration and development of biotechnology research in national research programs is now a prerequisite for current and most of the future science-based sustainable genetic improvement of crops for various purposes including, food and nutritional security, improving post-harvest and industrial qualities of cereals, horticultural and forage crops.

It is clear that smallholder farmers in African countries are currently not benefiting enough from modern biotechnology, which can be applied to transform their crop production and productivity and bring about livelihood improvements. Most national research programs in Africa have not yet acquired research and regulatory capacity and skills to integrate advanced science and cutting-edge technologies in their research portfolio to solve farmers' production problems. Although progress is registered in biotechnology capacity building in some countries, it is far from adequate. Governments' investment in agricultural research and development is generally low [9]. Crop productivity problems under smallholder farmers' conditions are often caused by low-level use of improved technologies and damage to crops caused by biotic and abiotic stresses as described earlier. The biotic and abiotic stresses challenging crop productivity are being tackled by biotechnology globally and several crop varieties with novel traits have been successfully developed and commercialized in more than 25 countries around the world to solve particular production problems of farmers.

1.3 Crop improvement programs in Africa

Food security and prosperity in Africa depend much on its agricultural performance. Ensuring sustainable development in agriculture is critically dependent on a sustainable technology supply and uptake. Despite the strong need for robust agricultural research, capable of tackling production constraints under challenging agricultural environments, African countries have not shown much progress in their national research capabilities to respond to food security issues and meet the overarching national strategic goals for sustainable development [9]. Strategic measures pursued to realize latecomer advantages in using modern biotechnology to enhance crop improvement and exploiting existing commercialized novel biotechnology products proven safe and impactful, is weak.

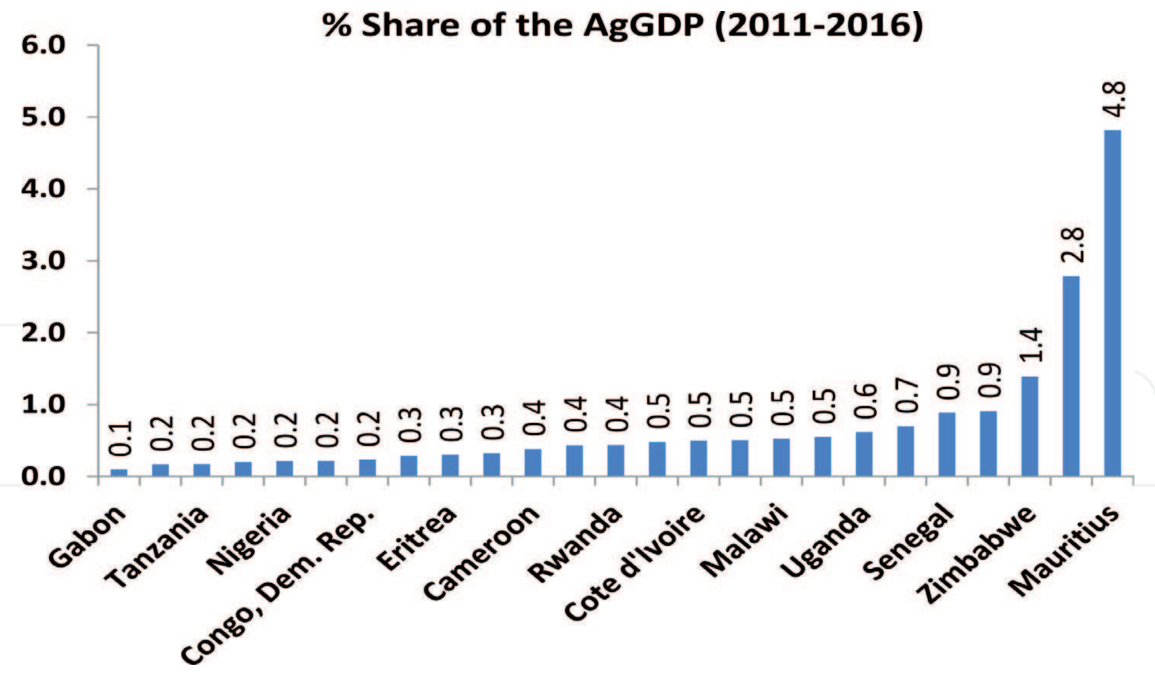

Figure 3.
Some SSA countries and their R&D investment share as a percent of AgGDP (except the top ranking the last three countries, all the others are selected only for representation of the rest). Source: Data sourced from ASTI [10].

Reports show declining government R&D spending in the agricultural sector recently from 0.59% in 2000 to 0.39% in 2016 in the SSA [10]. Thirty-three of the 44 SSA countries have less than the minimum investment target of 1% AgGDP (**Figure 3**) recommended by the African Union and United Nations [11]. Thus, most national programs in Africa were not able to maintain up-to-date capacity in trained human resources and facilities to translate scientific research into useful products impacting agricultural growth. Conventional crop improvement programs are increasingly requiring support from biotechnology to effectively respond to changing market demands. Therefore, African government should play a key role to strengthen national programs and maintain strong regional and global collaborative partnerships and expedite knowledge and technology transfer. Allowing more regional integration can help to ensure smoother collaboration, transfer of suitable technologies, data and information, and allows improved access to products at an affordable price and quality [12].

Most African countries have not created the necessary incentives for high-end modern biotechnologies to get well integrated in the research and development profile of national programs and create opportunities for new products to get to market. Instead, they depend on other countries that have decided to invest and strengthen their R&D. They are not taking advantage of this to enable national programs to expedite adoption and use of better and diverse technologies through quick testing and approval processes. Biotech products are rapidly expanding to include not only farmers' interest but getting more diversified targeting the interest of industry and consumers [13]. Therefore, a further declining trend of investment in agricultural R&D over the past 15–20 years in the developing countries with few countries in exception is alarming [14]. In countries with advanced economies where public financial outlay for R&D has lagged, the private sector has been investing heavily in genomic sciences and techniques that enable faster and more efficient delivery of improved crops to farmers, the value chain, and consumers, targeting business opportunities and crops with the greatest returns to investment [7]. However, many 'orphan' or underutilized indigenous crops in developing countries have been forgotten and their diversity is threatened [7]. It is highly challenging to rectify this imbalance between public and private research investment and ensure that crops including indigenous species are improved and conserved thus equally benefiting from modern biotechnology.

Against all odds and considerable skepticism in African countries even after three decades of the phenomenal growth of modern biotechnology and wider adoption of safe biotechnology crops globally, some countries have moved forward and strengthened capacity in biotechnology and related fields of biosafety, food safety, and intellectual property (IP) management to reap the benefits of integrating the advanced sciences. The recent progress in approvals of several biotechnology crops in Africa can reverse the delay in the near future [15–18].

2. Role of agricultural biotechnology: narrowing yield gaps

Rapid advancement is made in the field of biotechnology since the discovery of DNA and during subsequent advancements in molecular techniques and other "omics" technologies. This has ushered agriculture into a new era of technological frontiers to tap the latent potential of its biological resources in an unprecedented way, showing a new horizon of opportunities emerge to develop and modernize agriculture. Today, modern agricultural biotechnology encompasses a range of technologies including molecular breeding, fingerprinting, genomics, proteomics, genetic engineering, genome-editing, tissue culture and micropropagation techniques, and other advanced applications. This has empowered scientists, provided unlimited potential, to develop new strategies to harness genetic potentials for solving current and emerging crop production challenges. Therefore, biotechnology has provided a unique capacity to successfully fighting back the continuing battle against diseases, pests, and environmental stresses that are global threats to the survival of mankind. Genetic engineering, a part of modern biotechnology, involves the manipulation of the gene(s) of crop species by introducing, eliminating, or editing specific gene(s) through modern molecular techniques.

During the 1970s and 1980s, the public sector began supporting biotech research with lots of anticipations to advance the use of genetic engineering in agriculture soon to be taken over by the private sector. The first genetically modified (GM) plants were successfully developed as early as 1983 using antibiotic-resistant tobacco and petunia. In 1990, China started to commercialize GM tobacco for virus resistance followed by the Flavr Savr tomato in the United States. By 1995 and 1996, several transgenic crops were approved for large-scale use. Since the first commercial delivery in 1996, millions of smallholder farmers around the world have become beneficiaries of the multiple benefits from growing GM crops [19, 20].

Farmers are primary beneficiaries of the improved production and associated positive environmental, socio-economic, health impacts [21]. The rapid adoption and expansion of biotech crops reflect the substantial multiple benefits realized by farmers in industrial and developing countries. To date, of interest to farmers are several GM crops with enhanced input traits, such as disease (viral, fungal, bacterial) and insect resistance, herbicide tolerance, and resistance to environmental stresses such as drought, improved processing quality, improved product shelf life, and nutrient-enhanced crops available for commercial production.

Recent data [19] shows global acreage of only four biotech crops, corn, soybean, cotton, and canola has reached 190.4 million hectares in 2019 from 1.7 million hectares in 1996, which is on average 7.9 million hectares growth per year impacting crop production and productivity [22]. In recent years, the novel technique of genome-editing (GE) has been developed for targeted genome modification in plants with a high potential of increasing genetic diversity or correcting genetic

Country	GE crops researched, under testing, under approval process and/or approved	Commercialization (year)
Burkina Faso	Cowpea (insect resistance to *Maruca* pest); Bt cotton resistance to insect pest Bollworm) Rice (Resistance to *Xanthomonas oryza)*	Cotton (2008) suspended from production in 2016*
Cameroon	Cotton (stacked insect resistance and herbicide tolerance)	
Egypt	Wheat, Potato, Maize	Commercial production suspended in 2012
Ethiopia	Cotton (insect resistance); Enset (*Xanthomonas* wilt (BXW) resistance), Maize (insect resistance, drought tolerance)	Bt cotton (2018)
Ghana	Rice (nitrogen use efficiency/water use efficiency and salt tolerance), cowpea (insect resistance to *Maruca* pod borer insect pest), Rice	
Kenya	Cotton (insect resistance), Maize (insect resistance, drought tolerance, and stack of insect resistance and drought tolerance), Cassava (brown streak disease-CBSD), Banana (*Xanthomonas* wilt (BXW) resistance), Sweet potato (resistance to sweet potato virus disease), *Gypsophila* flower, *Sorghum* (biofortification)	Bt cotton (2019); Cassava Brown Streak Disease (CBSD) resistant Cassava (2020); Import ban on GM since 2012
Malawi	Banana plantain (bunchy top resistance), Banana (bunchy top disease resistance), Cowpea (insect resistance), Cotton (insect resistance);	Bt cotton (2018)
Mauritius	Sugarcane	
Mozambique	Maize (and stack of insect resistance, drought tolerance), Cotton (insect resistance)	
Nigeria	Cotton (insect resistance), Maize (insect resistance, herbicide tolerance HT Soybeans, Cassava (delayed postharvest starch deterioration), Cassava (Tuber size increase)cowpea (insect resistance to *Maruca* pest), *Sorghum* (biofortification), Rice (nitrogen use, water efficiency, and salt tolerance -NEWEST) Insect resistance and drought tolerance(Maize)	Cotton (2018) PBR Cowpea (2019) Bt Maize (2021)
South Africa	Cotton (insect resistance, herbicide tolerance multi-stack), Maize (insect resistance, drought tolerance, and stack of insect resistance and drought tolerance), Soybean (stacked trait with modified fatty acid composition); sugarcane (insect resistance); Wheat (insect resistance), Potato (insect resistance), Sugar beet, Tomato, Sweet potato, Cucurbits, Ornamental bulbs, Cassava; Apple, Strawberry, Apricot, Peach, Table grapes, Banana (data of traits for these crops has not been obtained).	Bt cotton (1997) Bt- Maize (1998) Bt- & Dt-Maize (2018?) Soybean (2001)
Sudan	Cotton (insect resistance)	Bt cotton (2012)
eSwatini	Cotton (insect resistance)	Bt cotton (2019)
Tanzania	Maize (drought tolerance; stacked for insect resistance and drought tolerance)	
Uganda	Banana (Xanthomonas wilt (BXW) resistance, Black Sigatoka resistance, Pro-vitamin A, Nematode and weevil resistance), Cassava (Cassava mosaic disease virus, Cassava whitefly resistance, Cassava mosaic disease virus, cassava brown streak disease virus resistance), Cotton (Bollworm resistance, herbicide tolerance), Maize (Insect resistance (stemborer), Drought tolerance, Drought tolerance and insect resistance (stacked genes), Rice (Nitrogen use efficiency, salt tolerance, water use efficiency), Sweet potato (Weevil resistance), Soyabean (Herbicide tolerance), Potato (Potato blight resistance).	

Source: ISAAA (2018), ISAAA Biotech Updates (2020), ISAAA Biotech Update (2021).

Table 2.
Genetically engineered (GE) crops researched, under testing, approval or commercialization in different countries of Africa.

defects. The simplicity and high efficiency of these tools have made it optimal for precise genome editing, heralding a new frontier in the—"Gene-revolution"—and in the development of modern biotechnology.

GM technology has been targeting some of the yield constraints and successful technologies have been commercialized in Africa for different crops such as insect resistance (maize, cotton, soybean, brinjal, cowpea), disease resistance (cassava, potato, sweet potato), better nutrition and quality (rice, potato, sorghum, banana). Some of these technologies are now successfully tested or grown in some countries of Africa (**Table 2**). Globally, by the end of 2019, a total of 71 countries (excluding EU countries) [19] issued regulatory approvals for GM crops, of these 11 were African countries. Total approval granted between 1992 and 2018 has reached 4349 from 70 countries (28 countries from EU) for food (2063), feed (1461), and environmental release or commercial cultivation (825) of GM plants [23]. In 2020 alone, 43 approvals were recorded for GM crops globally, involving 33 varieties from 12 countries, and eight of them are new varieties [22]. In 2019, four countries in Africa have given commercially approved for GM crops namely Ethiopia, (Bt cotton), Malawi (Bt cotton), Kenya (Bt cotton), and Nigeria (PBR cowpea) for the first time. Nigeria had additional approval for TELA maize in October 2021 and Kenya approved GM Cassava in June 2021. The TELA maize is built on the progress made from a decade of excellent breeding work under the WEMA project and working toward introducing the Bt- gene to WEMA, water-efficient varieties for drought tolerance [15, 16].

Despite several crops under testing for a long period, only a few have been commercialized in Africa (**Table 2**) [24]. In the SSA, South Africa has taken the lead with an estimated 2.7 million hectares covered with GM crops. It grows three commodities, namely cotton (100% cover), maize (85%), and soybeans (95%) of the total acreage [25]. Nigeria follows with three approvals (Bt cotton, PBR Cowpea, and TELA Maize) since 2018 [17], whereas Sudan stands second in acreage (about 192,000 hectares) from Bt cotton production.

Yield and quality improvements and associated economic benefits of growing GM crops have been the driving factors for biotech crops' rapid global expansion. A study conducted on GM crops and conventional hybrid (CH) maize yield differences across 106 locations and over 28 years in South Africa has shown a mean yield increase for GM over CH maize of more than 0.42 MT per hectare in addition to reducing yield risks [26]. Others reported [27] that GM technology adoption has reduced chemical pesticide use on average by 37%, increased crop yields by 22%, and increased farmer profits by 68%. According to the report, yield gains and pesticide reductions are larger for insect-resistant crops than for herbicide-tolerant crops, and yield and profit gains are higher in developing than in developed countries.

3. Farmers access to new agricultural technologies

Since the first field trial of a GM product back in 1987, the world has seen massive progress in the adoption of biotechnology crops and products and an increasing number of laboratory and field trials for a variety of novel GM products. Of the total global acreage (190 million hectares) of GM crops in 2019, the share of African countries is close to 3.0 million hectares only with South Africa taking the lead with 2.7 million hectares for HR-soybeans, IR/DT- maize and Bt cotton, followed by Sudan for 192,000 hectares of Bt- cotton [21, 28]. Currently, however, 13 biotech crops containing 13 traits in 13 countries are under different stages of research and evaluation in Africa [21]. Crops such as cotton, maize, cowpea, rice, sorghum, potato, sweet potato, cassava, banana, and sugarcane are either at the stage of

Confined Field Trials (CFT) or commercial production status [29]. Since 2018, four countries have entered commercial production for the first time in Africa namely, Nigeria (Bt cotton and PBR cowpea in 2018 and TELA maize in 2021), Kenya (Bt cotton in 2020 and virus resistant cassava in 2021), Ethiopia (Bt cotton in 2018), and Malawi (Bt cotton in 2018), after approval for the respective GM crops [19, 20]. Nigeria has made a move to become the first among African nations followed by Kenya that approved commercial use of GM food crops cowpea and maize.

Given global advancement in the use of GM crops, progress in Africa has been slower than expected [30, 31]. After three decades of global experience on the safety of GM crops and impressive impacts on the livelihood of millions of farmers, many countries still are postponing approvals of GM crops. Numerous health and environmental safety research reports have sufficiently confirmed the safety and desirable impacts of GM crops and their derived products [30–34]. Such scientific evidence have not challenged enough the lingering public perception and controversies around the risks of GM crops [35]. Instead, the overwhelming challenges faced by farmers make it difficult to believe these technologies can positively affect the situation of smallholder farmers [31]. However, scientists believe genetic engineering and genome-editing technologies will continue to impact the global economy with new momentum for more innovative technologies. Countries such as Ghana, Tanzania, Ethiopia, Mozambique, Uganda, and Malawi are in process of working on clarifying the biosafety context and developing a guideline for promoting genome-editing technologies in crop improvement [36].

3.1 Factors shaping access and availability of biotech products for smallholder farmers

The commercialization of already approved products is challenged by a wave of issues along the product commercialization chain. The national research capacity has been very critical to respond to farmers' needs for new technologies through creating awareness to the public, advising policymakers, testing of technologies, approvals, and helping access to proven technologies by farmers. In the same way robust regulatory system is needed to respond to applications based on scientific and empirical evidence. Often this has been a challenge in most countries since sufficient safety data generated can only be accepted and reviewed again by the regulatory agency of adopting country. Private and public sector developers apply step-wise review and decision processes to critically monitor the development of new products and to ensure that only good events are commercialized. Therefore, the intellectual property, product stewardship, and commercialization strategy become key parts of the product life cycle.

The Excellence Through Stewardship (ETS) [37], a global industry coordinated organization, identifies the key steps in the biotechnology product life cycle which includes the following: (i) research and discovery; (ii) product development; (iii) seed or plant production; (iv) marketing and distribution; (v) crop production; (vi) crop utilization; and (vii) product discontinuation (**Figure 4**). Product Stewardship and commercialization are key cross-cutting components along the product life cycle for the industry to remain innovative and viable. Successful commercialization of a GM crops, therefore, requires a well-planned strategy with sufficient information and expertise in a wide range of professions spanning from research and discovery to market and consumer interest.

In other words, success in commercialization also depends on downstream activities: functional seed systems and extension systems, strong technology demonstration, presence of reliable financial and marketing services, and the like. These are often weak in developing countries including most parts of Africa. The

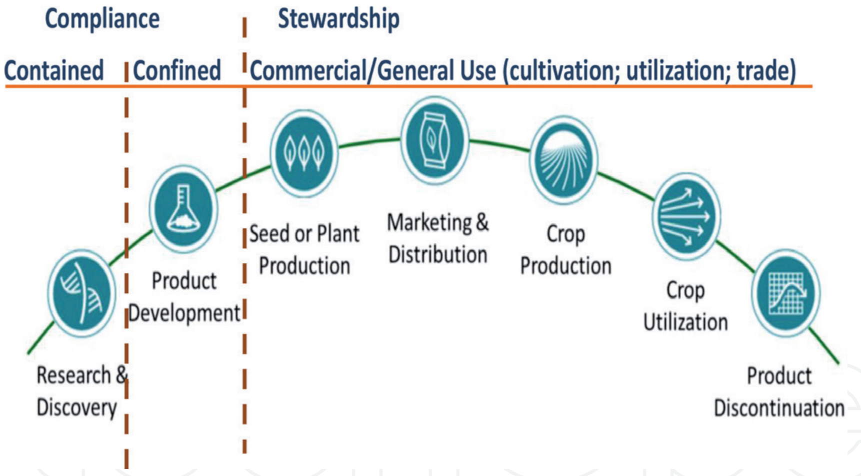

Figure 4.
Biotechnology product life cycle (Excellence Through Stewardship, 2018). Source: Excellence through Stewardship (2018).

blame on lack of political will, safety concern, or public acceptance for the delay in the adoption of deregulated products is often misleading. A recent assessment of stakeholders view on commercialization barriers of released biotech products shows socio-economic constraints, high cost of seed, weak certification of seed, weak private sector involvement, inadequate awareness of the technology, and best practices to be important [18, 24, 38, 39]. Thus, potentially a stronger public-private partnership in research, product development, and product commercialization in developing countries holds the key.

3.2 Challenges of scaling-up and utilization of biotech crops

Rigorous risk assessment studies take years to complete only to satisfy the benefit of the doubt. In Africa, many consider GM crops are intended for use in industrialized countries and are hence inappropriate for agriculture in Africa. There is a poor understanding of the use and potential impact of the technologies on improving productivity. In some countries, GM crops are considered a threat to biodiversity due to fear of replacing local or conventional varieties and indigenous crop species and thereby making farmers dependent on private seed companies. Limited research, regulatory and monitoring capacities, and anticipated loss of export markets with trade-sensitive countries also add up to the challenges against wider commercialization of the biotech crops [38]. In countries that have overcome hurdles of the regulatory system, rolling of GM crop commercialization and access by growers depend much on what happens downstream the pathway beyond product development, regulatory approval, and registration.

3.3 Enhancing regulatory decisions for improved access

Delayed decisions from regulatory agencies have a large, negative impact on the commercialization of new GM crop varieties around the world, but also in Africa [28]. While some delays can be sustained by some private sector developers, public sector developers are reliant on funding cycles and their projects are more quickly discontinued by indecision at regulatory agencies [40]. Regulators can strengthen decision-making by first reviewing the safety of new GM products and then linking the decision to national policy goals such as food security, sustainability, and the economic benefits to local farmers [41]. Linking regulatory decisions on GM plants to national policy goals, such as achieving the UN Sustainable Development Goals

(SDGs), will help to clarify which products benefit the community, the environment, and bring about economic growth [18].

3.4 Seed access

After going through national performance and verifications studies to satisfy national variety release and registration requirements [29], the product deployment is carried out by the technology owner, mostly a private company, through technology demonstration and demand-based seed supply. In this process, roles and stakeholder institutions change where the private sector, seed system, extension system, and other regulatory and financial institutions take over and function in subsequent steps. These transitions are not always clearly defined where the public sector is a major supplier of improved seed or where the seed sector is predominantly informal as in most African countries. Therefore, the commercialization of GM crops is overburdened with multiple issues of promoting new and approved products.

Weak seed systems and weak credit systems limit product access by farmers. A recent study on Bt-cotton hybrid seed access by farmers indicates that weak coordination among various stakeholders along the seed value chain is shown to exacerbate the problem of sustainable supply and wider utilization of the approved GM products [38, 39]. Lack of awareness of role players, inadequate demonstration of new technology to farmers as well as poor handling of the new technology by farmers, and poor extension schemes also contribute to the poor commercialization observed. Socio-economic constraints such as the high cost of hybrid seed, weak certification of seed, and inadequate awareness of technology and best practices (seed handling, agronomy, etc) can become important factors that can slow or block progress in some countries [38]. This also requires a stronger public-private partnership to advance the integration of modern biotechnology in the national R&D system.

4. Country case studies

4.1 Burkina Faso

4.1.1 Country progress

Burkina Faso has signed the Cartagena Protocol on Biosafety in 2003. It has an active and functional regulatory system hosted by the National Biosafety Agency (NBA) (Agence Nationale de Biosécurité, ANB) currently exercising Biosafety laws, regulations, policies, and guidelines in the country. In addition, at a regional level, the Economic Community of West African States (ECOWAS) has put regional framework and rules on biosafety. The NBA is hosted by the Minister of Higher Education but has consultative bodies such us National Scientific committee of Biosafety (comité scientifique national de Biosécurité = CSNB), Scientific and Technique Council, National observatory of Biosafety regrouping members from various ministries and non-governmental organizations.

4.1.2 Product development

The NBA has approved different research activities on GM crops. From 2006 to 2015 about 32 permits for different GM cotton activities related to BollgardII, RRF (herbicide tolerance), and the stack of both were made for import, laboratory studies, CFT, commercialization, and seed production activities. From 2010 to 2021, there were six permits given for *Maruca* Pod Borer resistant GM cowpea using

Cry1Ab or *Cry2Ab* genes for greenhouse and CFT. Other GM crop permits provided include for CFT on Bt Maize for insect resistance; greenhouse trial for vitamin and zinc-rich biofortified sorghum; greenhouse trials for leaf blight resistance in rice.

Only the Bt cotton Burkina Faso had reached the stage of commercialization and utilization. However, the Bt cotton cultivation was discontinued in 2016 due to cotton fiber length issues associated with the marketing of Bt cotton. Currently, most of the research activities are carried out in the greenhouses, cages, and CFTs. In Burkina Faso, stakeholders support the use of GMO as a solution to food security and for human disease control such as Malaria. The ANB has been undertaking sensitization of various public entities and various stakeholders since 2009 on biosafety actions as described by the national legislation and the Cartagena Protocol.

4.2 Ethiopia

4.2.1 Country progress

Ethiopia signed the Convention on Biological Diversity (CBD) in 1993, Cartagena protocol in 2000 which was approved by Parliament in 2003. The country adopted a tighter regulatory framework based on the Precautionary Principle (equivalent to "No GMO") ratified in 2009. The Biosafety bill was debated amended in 2016, known as 'A Proclamation to Amend the Biosafety Proclamation 2009'. In 2017, the National Biosafety Advisory Committee was adopted and in 2018 the country issues its Biosafety Guidelines. The amended law permitted scientists and institutions to do research and education pertaining GMOs. This allowed to establish legal and regulatory systems and build technical capacity to support and manage GMO issues and approved after CFT of three Bt cotton varieties in 2016 under the procedure of "Special permit", a provision in the Biosafety Law for research purposes. This was followed by 2 years of NPT across seven sites until 2018. The country approved two Bt cotton hybrids, JKCH-1050 and JKCH-1947 originally obtained from JK Agri Genetics Ltd., India for environmental release and variety registration. The accelerated commercial release demonstrated Ethiopia's government commitment to support the cotton development to satisfy booming textile industries [29].

4.2.2 Product development

Ethiopia considered biotechnology as one of the priority areas in its National Science and Technology Policy formulated in 1993 [42]. Due to interest to tighten the non-GMO stand, the prohibitive regulatory system delayed its overall engagement in modern biotechnology, postponed the use of available products, and hampered the development of the local capacity building. After approval of two Bt cotton Bollgard I type varieties in 2018, demand for Bt cotton seed for 2021/22 estimated at 3250 kg was requested for 1300 hectares. Some level of cross-border Bt cotton seed also takes place with Sudan and around 3055 hectares around border areas are already covered with such imported Bt cotton seed.

In 2008, the Biosafety Authority and the NBAC granted a "Special Permit" approval for CFT of drought-tolerant (WEMA) and insect resistant (TELA) maize for testing from 2018 to 2023. The isogenic conventional lines were evaluated for 2years in different locations before the CFT. The two-year CFT was started in 2019 under a controlled drip irrigation system for drought-tolerant trait evaluation and has shown very promising results. The stacked maize environmental release for both insect resistance and drought tolerance is awaiting approval using existing provisions.

In 2013, Ethiopia deployed GM technology for its indigenous Enset crop (also called "false banana") improvement in collaboration with the International Institute of Tropical Agriculture (IITA) for developing varieties with resistance to the deadly bacterial wilt disease caused by *Xanthomonas campestris* [43]. The collaborative research work had begun at BecA, Nairobi at IITA laboratory and later moved to Holetta Agricultural Biotechnology Research Center (NABRC) in Ethiopia in 2018 after approval was obtained for contained use (Contained Lab Permit). Approval for testing transgenic Enset under CFT is underway. Further to its endeavor in GM technologies, Ethiopia will soon engage in testing Late Blight Resistant (LBR) resistant cisgenic potatoes. Application submitted for CFT is awaiting approval.

4.2.3 Farmers access to new agricultural technologies

Approved Bt cotton hybrid seed demand is increasing but the hybrid Bt cotton seeds are not locally available and need to be imported from the technology supplier. But due to the decline in exports during the COVID-19 Pandemic, the Bt cotton seed supply system has suffered from foreign exchange restrictions to purchase seeds. The absence of local seed companies investing in Bt cotton seed has been one of the key challenges facing Bt cotton commercialization in Ethiopia.

Stakeholders across the cottonseed system must assess the most feasible pathway to ensure easy access to quality seeds at a reasonable cost, especially to smallholder farmers. Supporting cotton production with appropriate extension services and training of farmers and other relevant stakeholders for best practices is required to scaling-up the use of Bt cotton in the country. Developing innovative partnerships with technology developers to enable local Bt cotton hybrid seeds production will help to achieve affordable and sustainable access to GM technology.

4.2.4 Public perception and acceptance of GMOs

There is no clear data concerning the changes in the public acceptance of GM technologies in Ethiopia. However, the transition at policy and political levels is remarkable; from a stance of "GMO free" advocacy to one with pragmatic consideration to taking advantage of changes and prospects at the global level. The public perception is expected to evolve considerably due to growing global biotechnology importance in promoting food security in the wake of climate change. However, the recent movement following a report by the USDA that recognizes Ethiopia's commitment to implementing the amended protocol and embarking on some GM crops, has sparked severe criticisms against GMOs development in the country [44]. There has been a steep rise in anti-GMO comments following the USDA announcement [45]. It requires to provide the right information to the public and creating the right and positive public perceptions to help the right policy measures and institutional function with respect to biotechnology products.

4.3 Kenya

4.3.1 Country progress

Kenya is among the first African countries that signed the Cartagena Protocol on Biosafety in 2002. It also set up a national biosafety regulatory authority followed by a Biosafety policy signed into law in 2010 [46]. The exercise of dealing with GM products has seen many challenges such as the one when the government through the Ministry of Health instituted a Moratorium on the import and trade of GMOs on November 21, 2012, an embargo that remains in force to this day [47].

To date, two crops have been approved for commercialization use in Kenya and these are the Bt cotton hybrid, which was commercialized in 2020, and the improved cassava variety for resistance to Cassava Brown Streak Disease (CBSD). The NBA approved the application for environmental release for GM cassava containing Event 4046 in 2021 [48]. The GM cassava has increased root quality and higher yields [49]. Kenya is the first country globally to consider a request for environmental release involving GM cassava crops. Many other crops are now at different stages of regulatory approval. In the year 2021, 36 applications have been submitted for various crops under review [48].

4.3.2 Farmers access to new agricultural technologies

Kenya's GMO regulatory framework is robust and active. It is designed for regulating contained use, import, export and transit, environmental release, and labeling [46]. The emerging research area of gene-editing technologies in food and agriculture presents the newest frontier in the area of legislation and regulations in Kenya [46]. The NBA board has undergone timely training to equip them with knowledge on the understanding of the regulatory process of genome-edited organisms and products in Kenya [46].

4.3.3 Challenges in product commercialization

A strict and arduous regulatory approval framework remains one of the most important challenges to GMO adoption in Kenya [50]. So far, Bt cotton has been commercialized and the status of Bt-maize is at the NPT stage. Access to Bt cotton hybrid seeds, access to credit to purchase Bt cotton seeds, and lack of adequate monitoring data for Bt cotton is the weak side of the commercialization process.

Among the public institutions, Government Counties can play a role by forming cotton-producing clusters to support access to Bt cotton hybrid seed and inputs and access to the cotton market to encourage cotton-producing smallholders. This exercise on Bt cotton can also be helpful for similar efforts in the future for other new technologies [51].

4.3.4 Public perception and acceptance of GMOs

Public perception of GMOs in Kenya has been mostly negative for a long time due to bad press and negative publicity about GM products [50]. Kenya had instituted a moratorium on GMO import and trade in 2012 based on a study by Séralini et al. [52] that has since been disapproved. The damage, however, had been done and slowed progress in GM acceptance and adoption in the country. For most of the public, GMOs were dangerous, and disposed the government to take a reactive action. The growing awareness on the benefits of GMO technology in the continent and in Kenya in particular, is seeing an upsurge in attitude change for the better [50].

4.4 Malawi

4.4.1 Country progress

Malawi has made significant progress in biotechnology and biosafety since the ratification of the Cartagena Protocol on Biosafety in 2009. The country has domesticated the protocol by developing a legal and institutional framework for biosafety. Malawi developed its Biosafety Act in 2002, Biosafety Regulations in 2007, and enacted Biotechnology and Biosafety Policy in 2008. The CFT and NPT Guidelines, Trial Manager Handbook, and Inspectors Handbook were prepared in 2007. Since 2009, three permits to conduct GM crop trials have been issued under the Biosafety Act and approved its first Bt cotton for commercialization in 2018.

Other GM crops initiatives were transgenic Banana and Bt Cowpea both of which were terminated in 2019 due to lack of finance to support the research.

4.4.2 Farmers access to new agricultural technologies

Malawi's biosafety legal framework does not hinder the commercialization of approved technologies. Before varietal release of the Bt cotton hybrids, field demonstrations across key cotton-growing districts were done to help farmers with the potential of the technology (Bollgard II) and hybrid cotton varieties to help farmers build a positive perception about the benefits. However, the cost of Bollgard II hybrid cotton seeds was US$30 (MK 25,000) in 2021 became a concern. This means that for a hectare, farmers spend US$ 123.5 at a seeds rate of 4 kg/ha compared to US$ 1.2/kg for OPVs. The Bt cotton seed grown in Malawi are supplied from India and transport/import cost make seed prices higher and affects the adoption of the technology by smallholder farmers. Trainings on GM cotton seed multiplication for local farmers is underway to reduce cost on seed importation which is anticipated to result into affordable seed cost and improve its accessibility and adoption by smallholder farmers.

4.4.3 Public perception and acceptance of GMOs

In Malawi issues such as biosafety concerns, public acceptance, political will, and support influence the adoption of GM crops. Public opinion has not been contradicting to the introduction of GM cotton possibly due to the absence of known negative impacts on human health and good publicity during the field demonstration trials. There is high political will as government is working to restore the cotton industry in the country. Regulatory decisions have been science-based and risk assessment is done on case-by-case basis which has built level of trust for the technology among farmers and the public.

4.5 Nigeria

4.5.1 Country progress

Modern biotechnology regulation in Nigeria started in the early 1990s. The Convention on Biological Diversity (CBD), which Nigeria signed in 1992, identified GMOs or LMOs as a group of organisms produced by modern biotechnology that needed special attention because of their perceived adverse impacts on biodiversity and human health. Based on the Convention's recommendation, Nigeria ratified its biosafety framework in 2002. Consequently, research practice began in modern biotechnology, along with it the biosafety legal regime became apparent. Subsequently, Biosafety Law was put in place in April 2015 giving birth to the National Biosafety Management Agency (NBMA) for the implementation of the Act which also became amended in 2019.

4.5.2 Progress in product development

To keep abreast with advancements in modern biotechnology, Nigeria developed several guidelines including for GM Food, Feed Processing, GM Mosquito, GM Trees, Birds, Fish, and other animals. The country is the first in Africa to validate Genome editing guidelines during the last quarter of 2020. Several processing permits were granted for food and feed from GM maize, soybeans, and others.

Currently, Nigeria has several R&D activities at different levels: research, testing, pipeline, and commercialization. To date, NBMA has approved CFTs for the following crops: Bio-fortified cassava enhanced with pro-vitamin A, iron, and zinc; GM cassava resistant to cassava mosaic virus, Cassava brown streak disease virus, and enhanced with iron and zinc. Also, cassava was modified for higher starch; cowpea modified for resistance against maruca, HT soybeans; GM rice modified for nitrogen use efficiency, water use efficiency, and salt tolerance and GM maize for resistance to stem borer/fall armyworm and drought tolerance. The approval for commercial release has been for GM cotton (Bollgard II) to Bayer Agriculture Nig. Ltd./Mahyco Agriculture Private Ltd. in July 2018; cowpea modified for resistance to maruca insect pest and insect-resistant/drought-tolerant maize (TELA).

4.5.3 Farmers access to new agricultural technologies

The most important regulatory constraints are related to finance and laboratory facilities. The challenge in product commercialization of GM crops, as experienced in cowpea, is meeting the seed demands of farmers. Whereas in the case of cotton, the cost of seeds is not affordable by smallholder farmers, concerted efforts are being made by various platforms such as the open forum on agricultural biotechnology (OFAB), in Africa, Nigeria Chapter in collaboration with extension agents to let farmers get the right information and advisory services on biotechnology products. Nigeria's Biosafety Law requires mandatory labeling of products containing GM products or ingredients exceeding 4%, which restricts market access for GM products.

4.5.4 Possible pathways for commercialization

Access to improved seed is realized when the farmers can buy the seeds when they need them at an affordable price. Trust building is critical so that farmers as pragmatic as they are, have a positive attitude toward GM technology despite anti-GM campaigns and their misconceptions.

4.5.5 Perception and acceptance of GMOs

The Nigerian public has a mixed opinion about GM crops and their food products due to mixed information about the importance of biotech in promoting food security and the public concerns about its safety and health-related issues. A higher number of the public in Nigeria believe the country should domesticate the technology and build local capacity to develop GM crops [53]. For example, policymakers' and scientists' perception on GM technology was examined in Ghana and Nigeria using semi-structured interviews [54]. Results showed most respondents including policymakers believe the technology has great potential to solve agricultural problems. However, lack of trained personnel and weak institutional capacities present significant challenges to its wider utilization.

4.6 Sudan

4.6.1 Country progress

Sudan is a member of the Cartagena Protocol on Biosafety (CPB) since 2005. In 2010, a national biosafety law dealing with the application of modern biotechnology was issued and in 2012, Biosafety Council was formed. However, biosafety measures are only partially in place for the implementation of the Cartagena Protocol [55]. Despite such efforts by the government to develop the biosafety regulatory system, much remain to be done for the effective implementation of the protocol on biosafety [56]. The national biosafety law was amended to become

"Miscellaneous Amendments Law" (Unification of Environment Councils) and officially gazetted in Sudan [57].

The first open-pollinated Bt cotton genotype (CN-C02) carrying Bt gene Cry 1A from which is a specific toxin against larvae of bollworm was introduced by China-aid Agricultural Technology Demonstration Center (CATDC) and released for commercial production under the name Seeni1 in 2012. The Seeni1 variety was fast adopted at a commercial scale from 19,300 hectares in 2012 to 61,300 hectares in 2013 [58]. In 2016, the area almost doubled to 120,630 hectares. Seeni1 occupied about 25% of the country's total cotton cultivation area in 2012 and 97% in 2014 [59]. After the successful adoption of the first Bt cotton variety, Seeni1, another open-pollinated Bt cotton genotype from China (SCRC37) carrying the same gene of Seeni1 was released for commercial production and named Seeni2 in 2015. In the same year, two Indian Bt cotton hybrids; JKCH1947 (Hindi1) and JKCH1050 (Hindi2) carrying JKAL X-gene (Cry1Ac), were also released for commercial production [60]. The area under Hindi2 progressively increased from 7560 hectares to 33,600 hectares in 2021. The total Bt cotton cultivated area in Sudan since first commercial production in 2012 has grown to occupy about 98% of the total cotton area in 2021. In Sudan, cottonseeds represent a valuable oil and cake source. The major concern after the Bt cotton commercialization is the food safety of its byproducts; however, permissible levels for GMOs intended for direct use as food/feed needs approval from the national biosafety committee.

Recently transgenic cotton hybrid varieties carrying Cry1AC + Cry2A and glyphosate-tolerant trait (CP4 ESPS) were approved by the national biosafety technical committee in compliance with the national biosafety regulations for further testing. In Sudan, the establishment of national action plans for developing and promoting cotton exports and harmonizing its marketing policies are seen as crucial steps to restore Sudan's position in the international cotton market.

4.6.2 Farmers access to new agricultural technologies

In Sudan, Bt cotton is the only GM crop under commercial production since 2012. Additional new transgenic cotton varieties approved by the national biosafety committee are under testing and will enrich the Bt cotton variety options. The national seed industry of transgenic crops is not fully complying with the biosafety regulations due to the limited awareness of stakeholders involved in the seed industry. This has caused the sub-standard seed to be distributed by dealers.

Almost all Bt cotton seeds for open-pollinated variety are produced by the private seed sector under the governance of public institutions. The current situation of seed production could be improved with policy to guide and incentivize seed producers (public and private) for high-quality seed supply. The trend of seed demand growth in Sudan has been clear since Bt cotton adoption and requires comprehensive situation analysis to install a visionary seed production scheme.

On the other hand, not all smallholder farmers can access good quality seed because of limited financial support and a lack of farmers' organizations to obtain agricultural credit. Enabling policies are required for smallholder cotton farmers to overcome this problem and related marketing challenges.

4.6.3 Public perception and acceptance of GMOs

Sudanese public participation in GMOs use debates and its general awareness is limited. Either lack of understanding or misperception of the technology predominates. Public-wide formal and informal education on safety concerns (biosafety and food safety) and GMO utilization need to be strengthened. More engagement and participation of stakeholders along the cotton value chain would help to have a clear plan for promoting and sustainability utilizing the products of GM technology. Currently, the adoption of transgenic cotton in Sudan is farmer-driven and government intervention is highly beneficial to strengthen farmers' associations for market access and improving the benefits of Bt cotton to local farmers.

4.7 Uganda

4.7.1 Country progress

For the past 15 years, Uganda has been steadily integrating biotechnology into national development processes and developing local capacity. The Uganda national biotechnology strategy identified biotechnology as a tool to address challenges in the agricultural sector [61, 62]. The government has been providing support to build human resources and research infrastructure capacity to strengthen research development and innovation in biotechnology and played a dominant role in Uganda. R&D using modern biotechnology tools in crop science was initiated in 2003 at the National Agricultural Biotechnology Center. Other institutions like Makerere University and the National Agricultural Research Organization's (NARO) followed suit to join the effort. Several international and regional organizations also have been supporting national crop biotechnology R&D including USAID, Bill and Melinda Gates Foundation, ASARECA, CIMMYT, and Rockefeller Foundation. Through support from the government and development agencies, more than 10 research laboratories have been established for biotechnology research and development. The scientific community in Uganda has embraced biotechnology and is actively engaged in R&D using modern biotechnology and genetic engineering tools. There has been a growing application of tissue culture, molecular diagnostic tools, and the development of genetically engineered transgenic crops.

4.7.2 Biosafety regulatory system

Uganda ratified the Cartagena Protocol on Biosafety in 2001 [63]. In 2008, the government of Uganda adopted the National Biotechnology and Biosafety Policy to provide a regulatory and institutional framework for the safe and sustainable application of biotechnology for national development. Uganda's biosafety institutional framework includes national competent authority, national focal point, the national biosafety committee, monitoring and compliance mechanisms, and institutional biosafety committees.

The Uganda National Council for Science and Technology (UNCST) serves as the national competent authority and provides regulatory oversight for GMO research and development programs through the National Biosafety Committee (NBC). To support the NBC, biotechnology research institutions have established Institutional Biosafety Committees (IBC) to provide research biosafety stewardship and serve as a link between the research scientists and NBC. To provide a comprehensive biosafety regulatory framework for commercialization of GM crops, the Parliament of Uganda introduced the Genetic Engineering Regulatory Bill in November 2018 to be assented into an act. The Bill was seconded through stakeholder policy consultations to ensure establishment of an enabling national biosafety legislation.

4.7.3 Country progress

The first field trial of GM crops was conducted in 2007 on genetically engineered bananas for resistant to Black Sigatoka disease. To date, the NBC has approved 17 field research trials involving several GM crops mentioned below for various crops and traits (**Table 2**) [64–66]. The detailed summary of GM crops and incorporated traits is also partly presented in **Table 2**.

Like other breeding product pipelines, GM products require on-farm agronomic and agroecological tests under the guidance of approved biosafety guidelines. In Uganda, scientists are unable to proceed with product testing on farmer's fields to ascertain GM product performance due to a lack of national biosafety legislation and regulations. Crops such as banana (research, CFT and multilocation trials), Cassava (CFT, multi-locational trials), Cotton (CFT, multi-location trials), Maize (CFT and multi-location trials), Rice (CFT Research), Sweet potato (Greenhouse), Soybean (Greenhouse), Potato (CFT- Multilocation trials) have not been tested on farmers fields. Research on these crops has been conducted through joint collaborations involving local and international institutions such as NARO, IITA, AATF, Queensland University of Technology (QUT), Leeds University, Donald Danforth Plant Science Center (DDPSC), Bayer, International Potato Center (CIP), Makerere University, and Michigan State University.

5. Lessons learned and future prospects

Biotechnologies can help African country's efforts toward achieving social and economic development and contributing to the United National (UN) Sustainable Development Goals (SDGs) through improving agricultural productivity and increasing resilience to climate change impacts. As highlighted in the six case studies, countries in Africa are at various stages of biotechnology R&D and regulatory capacities. With the recent positive decisions made by the governments of several countries in Africa, the future holds prospects for the commercialization of GM products. Research, regulatory, and outreach capacity in modern biotechnology is seen as fundamental to the promotion of advanced science and technology in research programs including GMO and genome-editing research and development.

Identifying policy and regulatory gaps and adjusting to meet current and future needs would always be required to promote agricultural biotechnology for sustainable development in biotech and non-biotech countries. Proactively working toward building awareness of stakeholders and right public perception and relentless effort to capacitate policymakers would help to maintain the current efforts in improving political dynamics toward modern biotechnology and avoid sliding back to the old rhetoric led by postmodernist anti-GMO and anti-technology activism.

Since it took several years of negative publicity to entrench distrust among the public, it can only be undone with unyielding and consistent communication and outreach espousing, especially positive benefits to smallholder farmers and consumers and farmers as champions. Therefore, strong voices are necessary to champion the adoption of GMOs and genome-editing technologies in countries in Africa. Misinformation and disinformation, and competing interests inevitably complicate how modern biotechnology is viewed and its benefits are harnessed in Africa for smallholder farmers. The science communication should be amplified with messaging centering around a farmer and consumer benefits and contributions to UN Sustainable Development Goals (SDGs).

The transitions from product development to deployment and commercialization are often difficult in developing countries. Multiple institutions from the public and private sector including the farming communities are involved to operate. This needs to be well aligned and coordinated institutional functions are needed to ensure sustainable access and deployment of new technologies/products by smallholder farmers while keeping product integrity, quality, and excellence through stewardship. Experience shows the importance of careful handling and management of new technology with simultaneous preparation for the local seed systems to ensure that new products are consistently available and affordable by smallholder farmers. Alternative technologies are needed for widening the scope of adoption through a healthy market and avoiding negative perceptions to impinge on efficiency and competitiveness.

Farmers are willing to adopt impactful technologies that can enhance agricultural productivity and their livelihoods. However, closer consultation and understanding of their challenges is critical to foster and sustain repeated adoption of GM crops by farmers to convey a realistic understanding of the production and marketing challenges and receive necessary policy support. A clear monitoring strategy is needed for field management of GM crops and their sustainable use and impacts as well as co-existence in the farming systems of adopting countries.

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References

[1] AGRA Annual Report. 2017

[2] Jayaram K, Riese J, Sanghvi S. Agriculture: Abundant Opportunities. McKinsey Quarterly; 2010 https://www.mckinsey.com/featured-insights/middle-east-and-africa/africas-path-to-growth-sector-by-sector

[3] FAO and World Bank. Derived from Farming Systems and Poverty. Food and Agriculture Organization of the United Nations (FAO) & World Bank; 2006 Global Map of Irrigation Areas, FAO, NRLW & Johann Wolfgang Goethe University, Frankfurt am Main, Germany GAUL [Accessed: August 28, 2021]

[4] Sasu DD. Prevalence of food insecurity in sub-Saharan Africa as of 2019, by level. Statista 2021; https://www.statista.com/statistics/1190797/food-insecurity-in-sub-saharan-africa/ [Accessed: August 8, 2021]

[5] Baquedano F, Cheryl C, Kayode A, Jayson B. International Food Security Assessment, 2020-30, GFA-31. U.S. Department of Agriculture, Economic Research Service; 2020

[6] Nyiawung RA, Suh N, Bishwajit G. Trends in Cereal Production and Yield Dynamics in Sub-Saharan Africa Between 1990-2015. Journal of Economic Impact. 2020;**1**(3):98-107

[7] Anthony VM, Ferroni M. Agricultural biotechnology and smallholder farmers in developing countries. Current Opinion in Biotechnology. 2011. DOI: 10.1016/j.copbio.2011.11.020

[8] FAO. In: Elcio P, Guimaraes EP, Ruane J, Scherf BD, Sonnino A, Dargie JD, editors. Marker-Assisted Selection. Current Status and Future Perspectives in Crops, Livestock, Forestry and Fish. Rome: FAO; 2007

[9] FAO. The Special Challenge for Sub-Saharan Africa. High Level Expert Forum—How to Feed the World in 2050. Viale delle Terme di Caracalla, Rome, Italy; 2009

[10] Agricultural Science and Technology Indicators – ASTI, Boosting Investment in Agriculture Research in Africa Building. A Case for Increased Investment in Agricultural Research in Africa. Report Commissioned By Au-Safgrad; 2021

[11] UNECA. Towards Achieving the African Union's Recommendation of Expenditure of 1% of GDP on Research and Development. Addis Ababa: © UNECA; 2018 https://hdl.handle.net/10855/24306

[12] Eicher CK, Maredia K, Sithole-Niang I. Crop biotechnology and the African farmer. Science Direct Food Policy. 2006;**31**:504, www.elsevier.com/locate/foodpol-527

[13] National Academies of Sciences, Engineering, and Medicine. Preparing for Future Products of Biotechnology. National Academies Press, 2017; MLA 8th Edition (Modern Language Assoc.).

[14] Gert-Jan S, Beintema N. An Assessment of The Critical Financial, Human, and Institutional Capacity Issues Affecting Agricultural Research in West Africa: Synthesis and Policy Considerations. Background document for The World Bank. Washington, DC: IFPRI; 2017

[15] African Agricultural Technology Foundation (AATF). Strong supportive voices for biotechnology crucial for technology uptake in Africa. 2021. Available from: https://www.aatf-africa.org/strong-supportive-voices-for-biotechnology-crucial-for-technology-uptake-in-africa/

[16] Oloo B, Maredia K, Mbabazi R. Advancing adoption of genetically

modified crops as food and feed in Africa: The case of Kenya. African Journal of Biotechnology. 2020;**19**(10):694-701. DOI: 10.5897/AJB2020.17159

[17] ISAAA AfriCenter. 2021

[18] Gebre EK, Maredia K, Guenthner J, Koch M. Commercialization and deployment of genetically modified crops in Africa: Opportunities and challenges. African Journal of Biotechnology. 2022. DOI: 10.5897/AJB

[19] ISAAA. Accomplishment Report 2020

[20] ISAAA. Brief 55: Global Status of Commercialized Biotech/GM Crops. 2019

[21] ISAAA. Brief 54: Global Status of Commercialized Biotech/GM Crops. 2018

[22] Zhang J. Overview of global GMO development. AgroNews Annual Review. 2020

[23] Ichim MC. The more favorable attitude of the citizens toward GMOs supports a new regulatory framework in the European Union. GM Crops & Food. 2021;**12**(1):18-24. DOI: 10.1080/21645698.2020.1795525

[24] Turnbull C, Lillemo M, Hvoslef-Eide TAK. Global regulation of genetically modified crops amid the gene edited crop boom—A review. Frontiers in Plant Science. 2021;**12**:630396. DOI: 10.3389/fpls.2021.630396

[25] Venter C. Quick overview of GMOs in South Africa. AgriOrbit. 2020

[26] National Academy of Science. Chapter: 6 Social and economic effects of genetically engineered crops. 2016. In: Genetically Engineered Crops: Experiences and Prospects. National Academy Press; 2021

[27] Klümper W, Qaim M. A meta-analysis of the impacts of genetically modified. Crops. 2014. DOI: 10.1371/journal.pone.0111629

[28] Aldemita RR, Hautea RA. Biotech crop planting resumes high adoption in 2016. GM Crops Food. 2018;**9**(1):1-12. DOI: 10.1080/21645698.2018.1428166

[29] Akinbo O, Obukosia S, Ouedraogo J, Sinebo W, Savadogo M, Timpo S, et al. Commercial release of genetically modified crops in Africa: Interface between biosafety regulatory systems and varietal release systems. Frontiers in Plant Science. 2021. DOI: 10.3389/fpls.2021.605937

[30] Gbashi S, Adebo O, Adebiyi JA, Targuma S, Tebele S, Areo OM, et al. Food safety, food security and genetically modified organisms in Africa: A current perspective. Biotechnology & Genetic Engineering Reviews. 2021. DOI: 10.1080/02648725.2021.1940735

[31] Azadi H, Samiee A, Mahmoudi H, Jouzi Z, Khachak PR, De Maeyer P, et al. Genetically modified crops and small-scale farmers: main opportunities and challenges. Critical Reviews in Biotechnology, Early Online. 2015:1-13. DOI: 10.3109/07388551.2014.990413

[32] EUROPEAN COMMISSION (EU). A Decade of EU-funded GMO Research (2001-2010). 2010; https://www.researchgate.net/publication/233770770

[33] ISAAA Crop Biotech Update; 2021

[34] Bayer. GMO & Biotechnology Unlocking Hidden Potential. 2020; https://www.cropscience.bayer.com/innovations/seeds-traits/gmo-biotechnology.

[35] Mbabazi R, Dissanayake HG, Guenthner J, Maredia K. Perception of international stakeholders on genetically modified organisms (GMOs). Asian Biotechnology and Development Review. 2016;**18**(2):51-57

[36] Thompson T, Gyatso T. Technology adoption for improving agricultural productivity in Sub-Saharan Africa. In: 021 Virginia Tech College of Agriculture and Life Science and Virginia Tech Foundation. 2020 Available from: https://globalagriculturalproductivity.org/technology-adoption-for-improving-agricultural-productivity-in-sub-saharan-africa/

[37] Excellence Through Stewardship (ETS). Guide for Stewardship of Biotechnology Derived Plant products. Washington DC: Excellence Through Stewardship; 2017

[38] Mbabazi R, Koch M, Maredia K, Guenthner J. Crop biotechnology and product stewardship. GM Crops & Food. 2021;**12**(1):106-114. DOI: 10.1080/21645698.2020.1822133

[39] Alhassan SW, Anthony VM, Rudelsheim P. Implementation of stewardship in African agricultural public research and development institutions. Journal of Agricultural Biotechnology and Sustainable Development. 2018;**10**(5):97-103

[40] Morris and Thomson. Genetically modified crops commercialized in South Africa. In: Wambugu, Kamanga, editors. Biotechnology in Africa: Emergence, Initiatives and Future. Springer; 2014

[41] Raybould A. Improving the Politics of Biotechnological Innovations in Food Security and Other Sustainable Development Goals. Transgenic Res: Springer; 2021

[42] Waktola A, Tsegaye B. Biotechnology related policy, management and negotiation competence: Case Study from Ethiopia. In: NORAGRIC, Center for International Environment and Development Studies. Norwegian University of Life Sciences, Ås. Noragric Report No. 14-B. 2003

[43] IITA Blogs. Project to Save Enset—Ethiopia's Ancient False Banana from Deadly Bacterial Wilt Disease Star. IITA.; 2013

[44] Sida T. Will Ethiopia be a springboard or a stonewall for GM crops in Africa? Nature Biotechnology. 2021;**2021**(39):147-148. DOI: 10.1038/s41587-021-00827-5

[45] USDA Foreign Agricultural Services. Agricultural Biotechnology Annual Report. Ethiopia. Report Number: ET2019-0010; 2020

[46] Biosafety News. 2021. Available from: https://www.biosafetykenya.go.ke/images/newsletter2021/NBA-BIOSAFETY-NEWS-5TH-EDITION.pdf

[47] USDA-FAS. Agricultural Biotechnology Annual; Agricultural Biotechnology, Country: Kenya; Report Number: KE2020-0008Annual. 2020. Available from: https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Agricultural%20Biotechnology%20Annual_Nairobi_Kenya_10-20-2020 [Accessed: September 25, 2021]

[48] National Biosafety Agency. NBA Board Approves Environmental Release Application for GM Cassava. Press Release. 2021. Available from: https://www.biosafetykenya.go.ke/images/NBA-Board-Approves-application-for-Genetically-Modified-Cassava-FINAL.pdf [Accessed: September 25, 2021]

[49] XINHUANET News. Scientists Bank on GM Crop to Lift Cassava Industry in East Africa. 2021. Available from: http://www.xinhuanet.com/english/africa/2021-07/06/c_1310044498.htm [Accessed: September 25, 2021]

[50] Maina J. Bad press and wild claims have unfairly slowed GM crops on the continent, African Scientists say. Alliance for Science (cornell.edu). 2021

[51] Silas DO, Maredia K, Kedisso EG, Guenther J and Jeremy O. Value-chain of

cotton industry in Kenya with focus on product stewardship for timely provision of certified quality seeds to farmers. (In preparation).

[52] Séralini GE, Clair E, Mesnage R, Gress S, Defarge N, Malatesta M, et al. Long term toxicity of a Roundup herbicide and a Roundup-tolerant genetically modified maize. Food and Chemical Toxicology. 2012;**50**:4221-4231

[53] USDA. Agricultural biotechnology. Nigeria approves the commercial release of Bt. Pod-Borer Resistant Cowpea. 2019:1-13

[54] Adenle AA. Stakeholders' perceptions of GM technology in West Africa: Assessing the responses of policymakers and scientists in Ghana and Nigeria. The Journal of Agriculture and Environmental Ethics. 2014. DOI: 10.1007/s10806-013-9462-y

[55] Sudan Fourth National Report under Cartagena Protocol on Biosafety. 2019

[56] Ali AM. Biosafety and biosecurity in countries with low resources—Sudan as an example biosafety. 2013, 2013;**2**:1. DOI: 10.4172/2167-0331.1000105

[57] Gazette No. 1091: Miscellaneous Amendments Law—(Unification of Environment Councils) of 2020—Legislation No.3 of 2020

[58] Naglaa AA. The story behind Bt cotton: Where does Sudan stand. GM Crops & Food. 2014;**5**(4):241-243. DOI: 10.1080/21645698.2014.997119

[59] Ali AM. et al. Submission of Application to the National Biosafety Council, Ministry of Environment, for the Approval of the release into the Environment of a Bt Cotton Variety Seeni, 2012

[60] Ali AM., National Variety Release Committee Meeting, A Proposal for the Release of an Open Pollinated Bt Cotton (*G. hirsutum*) Variety for Production in the Sudan, 2015

[61] Ecuru J, Naluyima H. Biotechnology developments in Uganda and associated challenges. African Crop Science Journal. 2010;**18**(3):133-139

[62] Agaba J. GM Crops: Kenya and Nigeria Progress as Uganda Falters. 2021; https://allianceforscience.cornell.edu/blog/2021/08/gm-crops-kenya-and-nigeria-progress-as-uganda-falters/

[63] Muheebwa H. Uganda Parliament Passes Bill To Promote Use Of Genetically Modified Materials, Biotech. For Intellectual Property Watch 2. International IP Policy News. 2017. Available from: https://www.ip-watch.org/2017/11/03/uganda-parliament-passes-bill-promote-use-genetically-modified-materials-biotech/

[64] Zawedde BM, Kwehangana M, Oloka HK. Readiness for environmental release of genetically engineered (GE) plants in Uganda. Frontiers in Bioengineering and Biotechnology. 2018;**6**:152. DOI: 10.3389/fbioe.2018.00152

[65] Afedraru L. Uganda's scientists strive to use biotechnology to solve agricultural, health and environmental challenges. Genetic Literacy Project. 2018 https://geneticliteracyproject.org/2018/05/31/ugandas-scientists-strive-to-use-biotechnology-to-solve-agricultural-health-and-environmental-challenges/

[66] Muhumuza JR. Uganda's Biotech Research: More Than Just Untapped Potential 2021; https://allianceforscience.cornell.edu/blog/2021/03/ugandas-biotech-research-more-than-just-untapped-potential/