CHAPTER 4

Optimizing Biotechnology Paradigms and their Application for Agrifood Systems Transformation in Africa

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Introduction

Africa's population, which currently stands at about 1.55 billion, is projected to reach 2.5 billion by 2050 (Seijger et al. 2025). This vast population must be adequately ensured of food and nutrition security. Unfortunately, statistics indicate that about 25 percent of the continent's population is faced with hunger and undernourishment/malnutrition (with 30 percent of children stunted). This results in poor health and well-being, along with a chronic dependence on food imports – projected to cost US$150 billion[1] by 2030 if the imbalance is not addressed (AUC and AUDA-NEPAD 2024). Although the continent is endowed with vast arable land, a treasure trove of agrobiodiversity, and diverse agroecological settings conducive to the production of a wide array of crops to support its population, these resources have yet to be translated into resilient and sustainable agrifood systems to adequately address the needs and demands of the African people (Hamann 2020). Only a few species (about 20 species, mostly of high-calorie crops) from a potential 7,000 species account for 90 percent of food consumption on the continent (FAO 2023; Johns et al. 2013). By implication, Africa has yet to efficiently leverage most of its traditionally cultivated food, notwithstanding the longstanding adaptation and nutritive value identified in several species, rendering them largely neglected and underutilized crops.

African agriculture is dominated by smallholder farmers who remain insufficiently empowered because the continent has not fully enabled them to benefit from science, technology, and innovation (STI) to become globally competitive. For high-impact, transformative change, the facilitation of STI to address smallholder farmers' needs must be executed through a robust restructuring of the farming sector. The continent is characterized by low performance in the agriculture sector (crops, forestry, livestock, and fisheries) (AUC and AUDA-NEPAD 2024) with productivity well below world average levels due to a variety of factors such as poor soil fertility (Figure 4.1), abiotic stresses, more virulent biotic stresses (including invasive species like the fall army worm), and low use of inputs. Climate change has further intensified these challenges through more frequent and severe weather extremes, even though less than 4 percent of the factors causing them originate from the continent (Bedair et al. 2023). African smallholder farmers have traditionally tended to compensate for low yields in crops by placing more land under cultivation. However, with limited land and water resources available to a growing population, producing more food by expanding the land area under cultivation is simply not sustainable (Seijger et al. 2025).

Breeders and geneticists have advanced crop improvement through conventional approaches while also contending with the constraints of cost and efficiency. For instance, the genetic dissection of traits, especially those involving multiple genes, is complicated to manipulate in conventional breeding programs, necessitating a search for new paradigms to address this challenge (Buch et al. 2023; Tester and Langridge 2010). Biotechnology has rapidly evolved in the last 30 years to strengthen our understanding of the molecular basis underlying trait expression and, by extension, crop and animal productivity. As a discipline, biotechnology has been credited with the innovative strategies and concepts that have revolutionized animal and crop breeding. A review of advances in biotechnology has raised hopes for improved agricultural development, given its strong potential to address challenges related to food system resilience, both globally and, in particular, across Africa. The integration of biotechnology in agriculture has resulted in increased trade opportunities and economic development in the Americas and Asia, where it has been widely adopted (Otero 2008).

The global agricultural biotechnology market was valued at $29 billion in 2021 and is projected to reach $65 billion in 2031. Africa accounts for a small fraction of that, with a projected market of $871 million in 2025, indicating that it is gaining traction but at a slow pace. Arimany-Serrat et al. (2024) examined the relationship between resilience and sustainability (synergies, frictions, and conceptual overlaps), indicating that from a normative perspective, the desirable optimum is a system that is both sustainable and resilient. However, a complex mix of factors (economic, social, and environmental) could result in a system that has either sustainable resilience or resilient sustainability, depending on what is prioritized (Grumiller et al. 2022). Biotechnology paradigms have evolved rapidly over the past 20 years through technologies, techniques, and strategies that have enhanced opportunities for the novel delivery of fit-for-purpose and robust products in agriculture, health, and allied industries. These paradigms include the application of concepts that explore a combination of

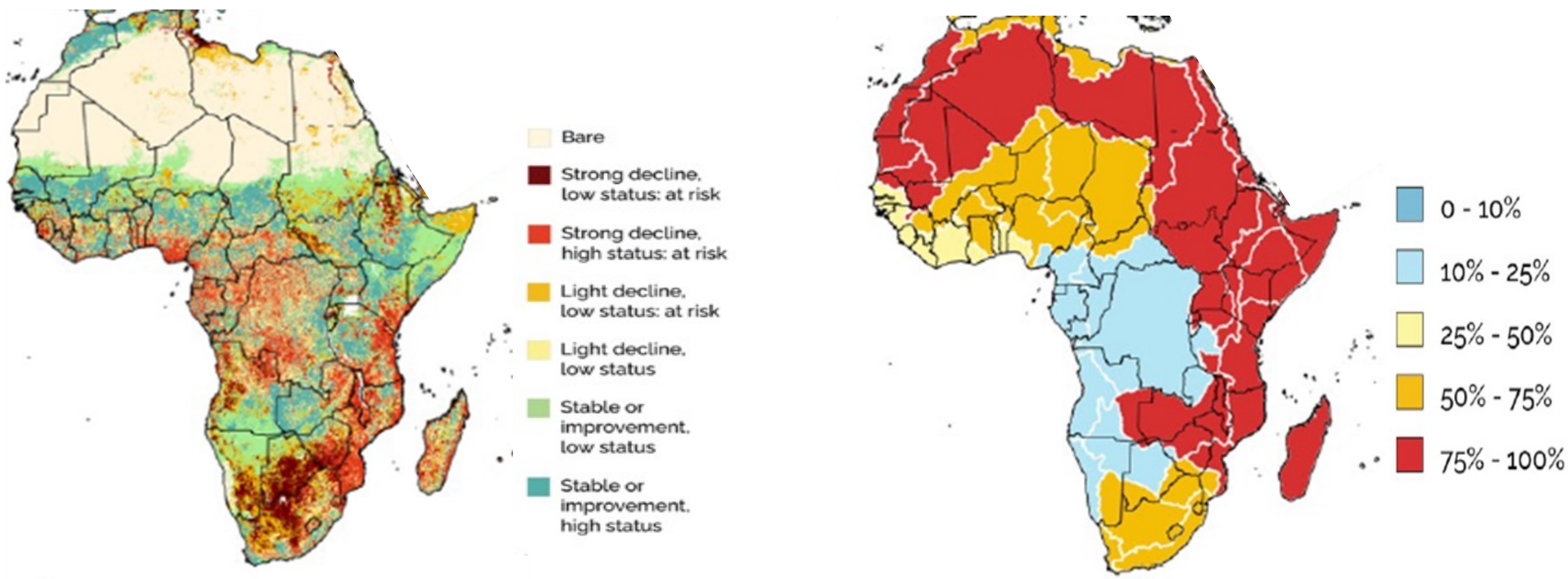
1 All dollars are US dollars.

approaches that maximize selection for the best genes/alleles across the genome to drive the development of resilient and durable products that support long-term benefits and sustainability. The successful optimization of biotechnology approaches has drawn on best practices such as the use of major genes as transgenics to enhance resilience within robust and diverse genetic backgrounds; the application of pangenome analysis to broaden genetic diversity; the exploration of haplotype-based selection to identify optimal allele combinations for greater genetic gain and trait stability; and the adoption of sound stewardship principles to ensure product sustainability and maximize benefits for farmers.

Under the 2025 Comprehensive Africa Agriculture Development Programme (CAADP) Kampala Declaration (post-Malabo agenda), biotechnology has been prioritized and positioned as a major intervention to contribute to building resilient and sustainable agrifood systems in Africa, with the aim of increasing food production by 45 percent by the year 2035. In line with commitments made during the Africa Union (AU) Extra-Ordinary Summit that gave rise to the CAADP Strategy and Action Plan (2026-2035), this chapter seeks to appraise the status of biotechnology applications on the continent, with a particular focus on identifying appropriate approaches that can efficiently build agrifood systems to contribute to some of the milestones envisaged in the CAADP Strategy. Some pertinent questions are relevant to this process.

First, what are the realistic prospects of exploring biotechnology to address smallholder farmers' needs in Africa? There has been much emphasis in the public domain on genetically modified organisms (GMOs), but less on other key elements and components of biotechnology that are relevant to the main issues

FIGURE 4.1—LAND DEGRADATION STATUS (LEFT) AND PROPORTION OF ARID AND SEMI-ARID AREAS UNDER WATER STRESS (RIGHT) ACROSS AFRICA



Source: Coppus, forthcoming, modified to comply with UN, 2021.

Source: FAO and UN-Water, 2021 modified to comply with UN, 2021.

facing African agriculture. In this chapter, we articulate the potential benefits that biotechnology can offer Africa in catalyzing agricultural transformation.

Secondly, does the current state of biotechnology investment and development in Africa offer credible, substantial opportunities to enhance resilient and sustainable agrifood systems, so that they, in turn, can catalyze and accelerate economic growth in Africa as envisaged under the Africa 2063 agenda? This chapter assesses biotechnology techniques and innovative strategies that are crucial to addressing and effectively stimulating transformative change in key priority areas in the agriculture sector. The innovative strategies to be adopted as solutions must be embedded in system-wide paradigms for sustainable agricultural development. In the African context, the desired transformation of food systems envisions a technology-based, system-driven form of agriculture that promotes a shift from subsistence farming toward a predominantly agribusiness framework across the value chain. This model integrates efficiency, cost-effectiveness, resilience, stability, genetic diversity, and sustainability to enhance profit margins for all stakeholders – from farm (production) to fork (consumers).

Thirdly, given the significant prospects offered by biotechnology, a common question frequently raised is: why is Africa not harnessing the diverse portfolio of 21st-century biotechnology tools available to create the change we want in the agricultural economic sectors of the continent? The key challenges undermining biotechnology on the continent are extensively addressed in this chapter. We explore lessons from other regions of the world that could help build a strong trajectory for biotechnology to drive food systems transformation for Africa. We also review current policies and investment portfolios in biotechnology and related areas, drawing out key policy implications.

Agricultural Biotechnology: Status, Potential, and Opportunities to Contribute to the Sustainable Development of Africa

Biotechnology status

Biotechnology has evolved over several decades, leading to the development of diverse tools and techniques that have a wide range of applications in the agriculture sector. These include the use of microorganisms (e.g., in fermentation), protein markers (isozymes, allozymes), tissue culture techniques (for conservation, embryo rescue, cytological studies, double haploidy), molecular markers, genomics, bioengineering, genome editing, and other new breeding techniques (Kumar et al. 2024). These tools and techniques have contributed to significant advances in agriculture and have facilitated the development of desirable traits in plants and animals, and other ways of improving agricultural productivity (Das et al. 2023).

In agriculture, GM plants are one of the most notable products of biotechnology. GM plants are those whose genetic material has been altered using genetic techniques that do not occur naturally (Defez et al. 2024). In 2023, GM crop cultivation accounted for a combined area of 206.3 million hectares in 27 countries (Amanullah et al. 2024), notably in the Americas. Commercial planting of GM crops began in 1996, and by 2023, the area dedicated to GM crops worldwide had expanded 121-fold, covering about 13.38 percent of the planet's total agricultural land area (estimated at 1,542 million hectares) and underscoring the growing importance of biotech in global food systems transformation (Amanullah et al. 2024). Developed nations were at the forefront of GM crop cultivation until 2011, when the area under GM cultivation became nearly equal between developed and developing nations (James 2011). However, from 2012 onwards, the trend changed, with developing countries increasing their GM crop areas at a quicker pace, reaching almost 55 percent of the global GM crop acreage by 2023 (i.e., 19.8 million hectares more than developed countries). This indicates a notable shift in adoption patterns and the increasing contribution and importance of developing nations in GM agriculture.

Africa has been part of the progressive shift to GM agriculture in the developing world. For instance, in 2019, approximately three million hectares of biotech crops were cultivated in Africa (Verma et al. 2022). Across Africa, 11 countries (Burkina Faso, Egypt, Eswatini, Malawi, Ethiopia, Ghana, Kenya, Nigeria, South Africa, Mozambique, and Sudan) have approved the cultivation of biotech crops (Mmbando 2024). The biotech crops cultivated are targeted at biofortification, drought and herbicide tolerance, and disease, pest, and virus resistance. Notwithstanding the progress being made, biotechnology development and adoption in Africa are still slow (Kyetere et al. 2019) compared to the Americas.

South Africa was the first country in Africa to adopt biotech crops, having planted insect-resistant cotton in 1998. This was followed by the approval of the cultivation of herbicide-tolerant soybeans in 2001, and later by the commercialization of insect-resistant maize in 2003 (ISAAA 2019). South Africa is leading in the adoption of biotech crops and currently grows GM maize, soybean, and cotton, followed closely by Nigeria, which grows GM cowpea, cotton, and maize (Gbadegesin et al. 2022). Burkina Faso and Egypt commercialized biotech cotton and maize, respectively, in 2008. However, the cultivation of biotech crops in Egypt was stopped in 2012, partly due to the absence of a robust biosafety law governing genetically engineered products and because the country also had concerns over the strict regulations on GMOs in the EU, fearing this could affect its trade interests. The enthusiasm that followed the release of Bt cotton in Burkina Faso was dampened by product segregation issues that compromised fiber quality, highlighting the need for optimized biotechnology approaches in product development.

Sudan commercialized biotech cotton in 2012, followed by Eswatini and Nigeria in 2018, and Malawi and Ethiopia in 2019 (Kedisso et al. 2022). Additionally, in 2021, Nigeria became the first country to commercialize GM pod-borer-resistant cowpea in Africa, followed by Ghana in 2024 after it met all the regulatory requirements (Mockshell et al. 2024). Kenya, Ethiopia, and Mozambique approved GM maize for cultivation recently. Ongoing GM research is concentrated on the development of drought-resistant crops and biotic stress tolerance in many African crops such as bananas, cassava, sorghum, and sweet potatoes (Tripathi et al. 2019). Genetic engineering methods have also been utilized in the biofortification of crops to raise micronutrient levels (Zn, iron, provitamin A, etc.) in human diets (Aggarwal et al. 2023; Koç and Karayiğit 2022). Experts predict that the market for genetically modified crops in Africa, which was initially valued at $615.4 million in 2018, will grow by 5 percent in 2025, reaching an estimated $871 million (Farmers Review Africa 2025), supporting the huge transformational potential of biotechnology in catalyzing the development of the agricultural sector in Africa.

Biotechnology has facilitated the creation of novel therapies and diagnostics by utilizing enzymes, microbes, proteins, and the metabolic processes of plants and animals (Masehela and Barros 2023). Africa is regarded as having the greatest potential to benefit from the adoption of biotech crops due to the widespread challenges of hunger, poverty, and malnutrition on the continent. The 21st century has witnessed major advances in molecular techniques and tools that are rapidly transforming application strategies, further enhancing the potential of biotechnology to address food and nutrition

Key techniques driving biotechnology potential in agriculture

Advances in biotechnology have been based on innovative molecular techniques and bioscience tools that have facilitated precision, speed, efficiency, and novel solutions to substantially address the diverse challenges undermining agricultural productivity (Ahlawat et al. 2024; Fairley-Grenot and Ftse 2018). These techniques and tools have facilitated better understanding of biological systems, thus enhancing the capacity to manipulate them genetically for improved physiological and metabolic processes responsible for agricultural productivity. About 50 percent of challenges associated with crop performance in the field are related to genetics. A further 10 percent of challenges are associated with the science of delivery, which is related to genetics and tools that support physiological growth and development (e.g., sterile female lines in hybrid production, tissue culture in micropropagation, etc.). About 10 percent of factors related to improvement in environmental conditions for good crop performance can also be addressed by genetics (bioengineering of microbes for soil improvement and remediation). By implication, about 70 percent of the issues linked to food systems resilience can be addressed through molecular techniques and biological tools, which demonstrates the strong potential of biotechnology in driving agricultural transformation. Africa should prioritize the following key techniques/tools, which have been crucial in biotechnology development, for further capacity development in order to explore their full potential.

Tissue culture

Tissue culture is a technique that is used to grow plant cells, callus, protoplast, meristem, tissues, and organs in controlled nutrient medium in vitro (Lone et al. 2020). It is one of the oldest applications of biotechnology that has gained importance in cytogenetic studies, population development for breeding, embryo rescue, and micro-propagation of propagules, especially in root and tuber crops, where plant multiplication ratio is much lower compared to grain crops. It has been used for germplasm conservation, removal of virus when generated from meristematic tissues, organ regeneration, and somatic embryo formation for propagation (Singh et al. 2023; Tripathi et al. 2022). It has been fully explored as a technique in genetic engineering processes. In breeding, it has been used to accelerate the development of inbreds through haploidy/double haploidy

(DH). This has facilitated the rapid development of hybrids. The development of inexpensive tissue culture methods and sourcing of alternative low-cost gelling agents, carbon sources, liquid media, and reusable glass beads has offered greater opportunities for the wider application of tissue culture in Africa (Lone et al. 2020).

Molecular markers and GBS

Molecular markers are DNA sequences that have been widely applied to identify genes involved in traits of interest in breeding (Ahmar et al. 2020). The concept of molecular markers was applied in genotyping to understand the genetic basis underlying trait expression, the mode of action involved, and to aid their tracking in breeding programs. The development has evolved over the decades with the development of different types of molecular markers from hybridization-based markers to polymerase chain reaction (PCR)-based markers, and later single nucleotide polymorphism (SNP) markers (Ahlawat et al. 2024). Advances in next-generation sequencing technologies have made genotyping-by-sequencing (GBS) a faster and more efficient method for genotyping, generating large volumes of SNP data in the process. They have been efficiently used in studies for genetic and quantitative trait loci (QTL) mapping (gene detection), evolution, as well as in research on phylogeny, heterosis, and genetic diversity. Markers and GBS are facilitating molecular breeding by enhancing selection for favorable alleles driving genetic gain (Kumar et al. 2024).

Recombinant DNA (rDNA)

This is a genetic engineering technique (also called genetic transformation) that allows a foreign gene or genes to be inserted into a genome. It uses laboratory tools to integrate DNA (normally termed rDNA) into an organism (MacKelprang and Lemaux 2020). A soil bacterium (*Agrobacterium tumafaciens*) or particle bombardment using the gene gun is normally used for this procedure. The rDNA is inserted randomly into the genome. After transformation, genome sequencing can then be used to identify the exact location. This technique has been successfully used to develop products in the Americas, Asia, and Africa (MacKelprang and Lemaux 2020). It has been applied primarily for commercial traits such as insect resistance, herbicide tolerance, and unsaturated oil.

SDN biotechnology techniques

Site-directed nuclease (SDN) techniques encompass the different approaches applied in genome editing. Genome editing is a highly promising technique that offers new opportunities to enhance the use of biotechnology in creating unique products with greater precision and efficiency. It involves using custom-designed DNA-cutting enzymes (nucleases) to make precise changes to DNA sequences at a specific targeted location in an organism's genome (MacKelprang and Lemaux 2020). Among the nucleases, the most successful, preferred, and widely used are clustered regularly interspaced short palindromic repeats (CRISPR)-associated proteins, with CRISPR-Cas9 being the most common (Tripathi et al. 2019). The advantage of the technique lies in the capacity to edit with or without foreign genetic material.

Omics technologies (OT)

Omics technologies (OT) integrate data from multiple platforms to interpret and discern the pathways involved in biological phenomena in a systems approach that gives insight into the structure, function, and dynamics of an organism (Nayak et al. 2021). They combine data from genomics (genes), transcriptomics (mRNAs), proteomics (proteins), and metabolomics (metabolites). The approach has improved understanding of the mechanisms and processes involved in systems biology, based on large-scale analysis. OT is used for improving crop productivity and understanding disease mechanisms in agriculture, and has the potential to be a game changer for enhancing food systems in Africa (Nayak et al. 2021). African crops have already benefited from the use of OT in building food systems resilience. Proteomic analysis has identified genes associated with disease resistance in African bananas (Soares et al. 2021; Tripathi et al. 2019). OT has also been used to identify proteins involved in starch biosynthesis, which has led to improvements in cassava products (Beyene et al. 2018). Transcriptomics, on the other hand, have been used to determine environmental stressors and the molecular mechanisms controlling drought tolerance in African millet. Metabolomics has been explored to enhance the nutritional value of crops (Beyene et al. 2018) through the identification of compounds associated with iron and zinc content in the African bean (Beyene et al. 2018).

Synthetic Biology

Synthetic biology (SynBio) is an upgrade of genetic engineering that encompasses the construction and design of new biological elements (e.g., cells, genetic circuits, enzymes) or the redesign of biological systems to facilitate novel and improved functions (Beyene et al. 2018). It does this by using existing biological building blocks to create new combinations not found in nature, or by building non-existent biological blocks to create new or natural functions. It essentially brings some additional power and improvement to other technologies by creating biological systems that may not exist in nature. It is useful for multigenic traits with complex modifications, as opposed to genetic engineering, which is highly successful for single genes and oligogenic traits. SynBio easily transfers multiple genes in a single transfer event or synthetically generates them (Roell and Zurbriggen 2020). Other applications include creating novel genomes from a set of standardized genetic parts, transferring them to an organism, and artificially creating genetic variation. The SynBio toolkit includes CRISPR-Cas9, Golden Gate, RNAi, Gene drives, Gene synthesis, and regulated promoters. SynBio was used to develop C4 rice involving five genes (Ermakova et al. 2020). The adoption of this technology has not yet gained traction in Africa due to regulatory frameworks and hurdles related to research capacity.

Priority constraints for biotechnology solutions in African agriculture

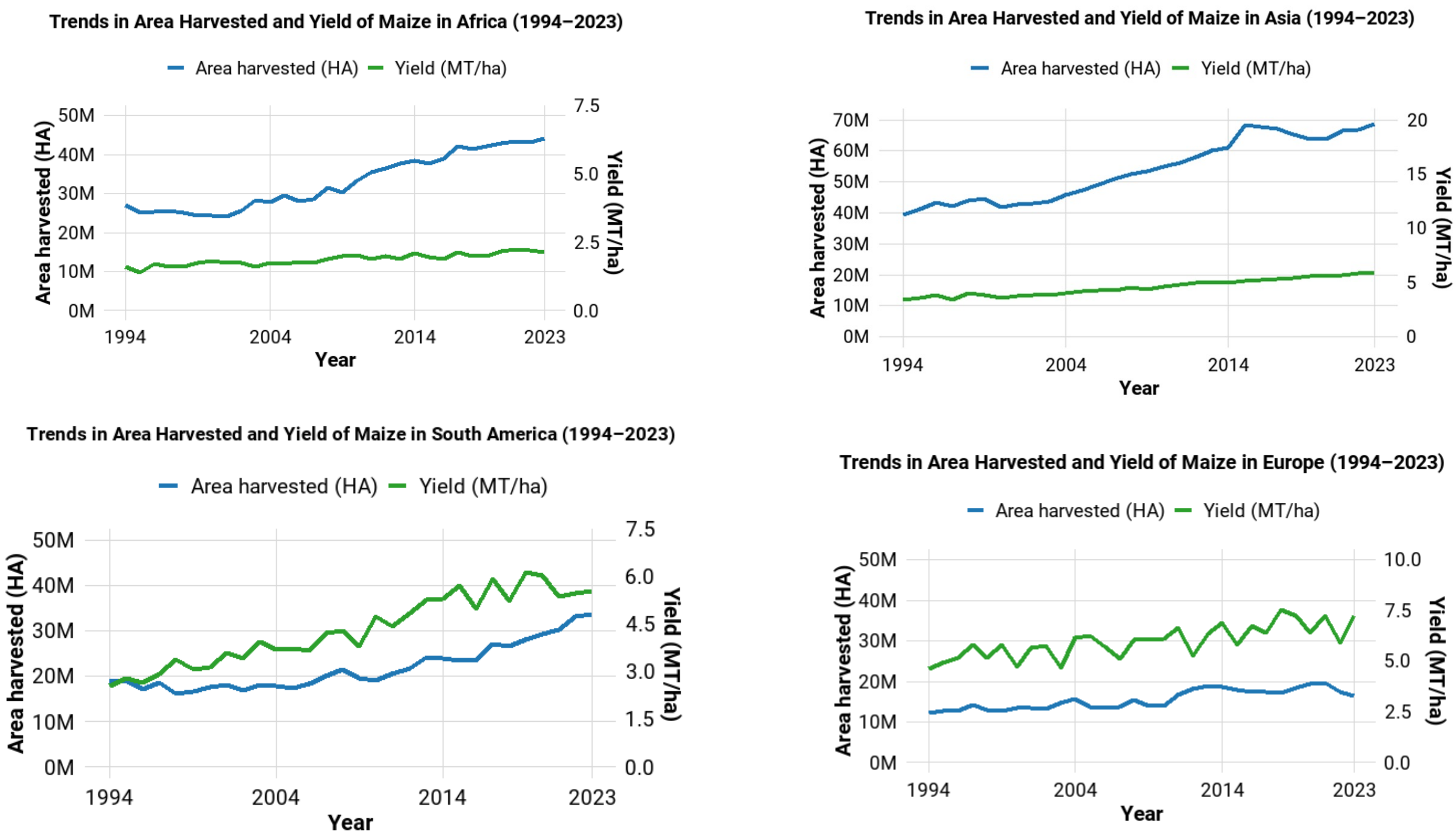
Different molecular techniques and biological tools have been deployed to provide biotechnology solutions for agricultural challenges. Their use has been most appropriate in the absence of conventional breeding solutions for productivity challenges in agriculture. Investment in agricultural development in Africa still lags behind other regions of the world. The majority of African countries did not achieve the Malabo Declaration target of committing 10 percent of the national budget to agricultural research and rural development. Given limited resources and infrastructure for deploying biotechnology, Africa must prioritize and strategically focus its agricultural transformation efforts on the key challenges that most strongly affect food and nutrition security for its growing population – while also stimulating broader economic growth. The three most crucial areas for biotechnology intervention based on these criteria are: yield gap, enhancing climate resilience, and combating malnutrition.

Bridging the yield gap

Yields of crops grown in Africa are typically lower than the global average, leading to food deficits on the continent (Tian and Yu 2019). For example, a longitudinal comparative analysis of maize yield (MT/ha) and harvested area (ha) from 1994 to 2023 across Africa, South America, Asia, and Europe uncovered varied agricultural development trajectories (Figure 4.2). In Africa, yields have largely remained around 2 MT/ha, while the harvested area has grown from about 25 million to over 40 million hectares, indicating a focus on extensive growth through land expansion as opposed to productivity gains (Chamberlin et al. 2014). Asia exhibits a dual-growth trend, with both area and yield increasing steadily; the area under cultivation expanded from 40 million to over 60 million hectares, and yield improved from approximately 4.5 to 6.5 MT/ha. In contrast, South America has seen substantial yield improvements, from roughly 3 to 6 MT/ha since the early 2000s, with only moderate increases in the cultivated area, suggesting a shift towards productivity-driven intensification (FAO 2025). Europe experienced modest yet consistent yield enhancements over the years, reaching up to 8 MT/ha despite the harvested area remaining almost unchanged, reflecting technological efficiency gains. These patterns imply that Africa's stagnation is more about structural barriers to adopting productivity-enhancing innovations than land expansion constraints. By learning from the experiences of Asia and South America, Africa can move toward agricultural intensification and harness biotechnology solutions to enhance the yield potential of African germplasm, improving adaptation and productivity under intensive production systems. Maize hybrids in Asia and the Americas have benefited from biotechnology techniques that have rapidly permitted increased genetic gain in only a few generations of breeding cycles (Andorf et al. 2019).

Yield, strictly speaking, is not a trait, as it is a product of many metabolic pathways driving several components. With increased advances in biotechnology (NextGen sequencing, bioinformatics, and omics), the complex pathways involved in yield dissection have become better streamlined and more efficient in exploring biological systems and identifying superior haplotypes associated with top yield performance. The best genetic gains and improved yields have been facilitated under biotechnology platforms in the developed world and in rapidly developing

FIGURE 4.2—TRENDS IN MAIZE YIELD (MT/HA) AND AREA HARVESTED (HA) ACROSS AFRICA, ASIA, SOUTH AMERICA, AND EUROPE (1994–2023)



Source: Authors' calculations based on FAOSTAT (2025).

countries. A study examining yield differences between GM crops and conventional hybrid (CH) maize across 106 locations over 28 years in South Africa revealed that GM maize yields were, on average, more than 0.42 metric tons per hectare higher than CH maize, while also minimizing yield risks (Kedisso et al. 2022). Transgene technologies have been deployed to close yield gaps. For example, the HB4 gene has been used to improve drought tolerance in wheat and soybean globally, with significant yield increases. Yields of GM HB4 wheat were 20 percent higher than those of conventional wheat in South America (Gutman 2021). The gene is now being explored for its potential to improve yields in Africa (e.g., Ethiopia). Additionally, other research has shown that adopting GM technology has led to a 37 percent reduction in the use of chemical pesticides on average, as well as a 22 percent increase in crop yields, and a 68 percent increase in farmer profits (Kedisso et al. 2022).

Agriculture in Africa is dominated by smallholder farmers who either have no access to or cannot afford inputs such as fertilizers and pesticides. However, biotechnology can reduce the impact of input constraints by developing crops that are pest-tolerant and efficient in their use of resources. Access to royalty-free technologies through non-profit development agencies in Africa is a way for farmers to access seeds sub-licensed to African seed entities at no extra cost for the trait. To facilitate ready access, these agencies are also building capacity in the seed companies to support improved production and availability of seeds to African farmers. Biotechnology has mapped genes that confer better nutrient use efficiency when used on marginal lands, leading to improved productivity.

Meanwhile, molecular breeding strategies have enhanced the selection of genes that enable the efficient use of nutrients (Khan et al. 2024). Genetic engineering has also been used to promote nutrient use efficiency (Lebedev et al. 2021). The bioengineering of soil microbes to enhance nutrient release is another example, applied to improve productivity under low-input production systems. Enhanced yields attributed to the improved varieties will also drive income growth among farmers. The additional income yielded from the extra output can offset the marginal cost associated with the higher cost of improved seed, leaving farmers with a positive net benefit. This approach can help alleviate concerns about burdening farmers with higher seed costs and prevent the exclusion of small-scale farmers from effective participation in agro-input markets.

Climate-smart agriculture and adaptation

The threat of climate change to food and nutrition security, as well as to in situ germplasm conservation, is increasing, highlighting the urgent need to develop resilient food systems (Jain et al. 2023; Smith et al. 2021). It is important to underline that insufficient soil moisture is one of the greatest problems facing agriculture in Africa south of the Sahara, and this is predicted to worsen with global warming arising from climate change. The identification of adapted germplasm has provided material for gene mining in the development of more adapted crops (Jain et al. 2023). Such materials have been used as parents for breeding improved and adapted varieties. Through biotechnology, several genes related to drought, heat, and flooding tolerance, and the mechanisms involved, have been identified and transferred into elite germplasm (Adhikari et al. 2017). For example, breeding for drought tolerance has been facilitated through genomic selection and marker-assisted breeding in pearl millet (Srivastava et al. 2022) using genes from the 'resurrection plant', Xerophyta viscosa. Early findings indicate that crops incorporating genes from Xerophyta viscosa exhibit strong tolerance to dehydration, heat, and salinity, signaling significant opportunities for using biotechnology in Africa to bioprospect potential genetic solutions for crop improvement (Farrant et al. 2015).

DroughtTEGO (drought-tolerant) maize was developed using molecular marker-assisted breeding in a public-private partnership coordinated by the African Agricultural Technology Foundation (AATF) (Obunyali et al. 2019). Results from the WEMA project, which developed maize with improved water-use efficiency, show that drought-tolerant crops designed to avoid yield penalties (that is, they maintain yields when moisture is sufficient) can achieve yield increases of 6–16 percent under optimal growing conditions with adequate moisture (Musimwa 2022).

Climate change brings not only drought and heat stress but also increased pest pressure. Genetic modification was used in developing TELA drought-tolerant maize (Box 4.1), which combines drought tolerance with resistance to stem borers and fall armyworm.

Another example is the development of cowpea varieties resistant to pod borers (Box 4.2). Biotechnology in general has made it possible to create crop varieties that exhibit traits allowing them to withstand stressors such as drought, cold, and salinity (Table 4.1). These characteristics have made it feasible to grow crops in challenging environments (Das et al. 2023). African agriculture is predominantly rainfed (95 percent), with only 5 percent under irrigation. Given the challenges of inadequate irrigation infrastructure and increasingly erratic rainfall due to climate change, drought-tolerant crops developed through biotechnology will remain essential for driving productivity in Africa, where farming depends largely on rainfall. Extreme weather conditions are also causing

BOX 4.1—GROWING INSECT-PROTECTED AND DROUGHT-TOLERANT TELA® MAIZE IN NIGERIA

Stem borer and fall armyworm are two major pests that reduce yields and grain quality in maize. To address these constraints, farmers spray their maize with costly, hazardous chemicals that have a limited impact in controlling the pests. Genetically engineered insect pest–resistant maize varieties with a drought-tolerant background, trademarked TELA®, have demonstrated high yields and good grain quality without the need for chemical pest control, based on efficacy data from confined field trials (CFTs) conducted in six countries in Africa south of the Sahara. On average, insect-protected (Bt MON810–traited) TELA® hybrids yielded 7.7 t/ha, compared with 5.4 t/ha for their corresponding non-Bt isohybrids under target pest infestation.

Currently, 15 TELA® Bt MON810/MON89034 hybrids with yield advantages ranging from 15 percent to 89 percent relative to commercial checks have been commercially released to smallholder farmers in Ethiopia, Kenya, Nigeria, and South Africa. Results of first-year commercialization of the TELA Bt MON89034 hybrids across four-major maize growing agroecologies in Nigeria showed that farmers who grew TELA® hybrids had a yield advantage of 88 percent (5.85 t/ha vs. 3.11 t/ha) and had net revenues that were 137 percent higher than farmers who grew other varieties, due to a 25.6 percent reduction in pesticide application costs. Recent socio-economic studies on similar TELA® MON9034 hybrids carried out in the Mpumalanga and Limpopo provinces in South Africa showed that smallholder farmers who had adopted TELA® maize since 2016 had seen productivity and income increase by 33–61 percent relative to non-adopters. Greater efforts are therefore needed to promote the adoption of TELA® maize in countries where the varieties have been released for commercialization.

BOX 4.2—YIELD PERFORMANCE OF POD BORER RESISTANT COWPEA (PBRC) IN THE FIELD

The Pod Borer Resistant Cowpea (PBRC) was developed to protect cowpea against the *Maruca* pod borer, a major pest that can destroy up to 80–100 percent of cowpea yields in the heavily infested savanna regions of West Africa. Farmers now only need to spray insecticides twice per season, instead of the usual eight times, reducing both costs and exposure to harmful chemicals.

National Varietal Performance Trials were conducted in Ghana (2022) and Burkina Faso (2024) to evaluate the yield performance of PBRC compared to elite commercial varieties. In Ghana, trials were carried out during the rainy season in pod borer-endemic areas across the Northern, Upper West, Northeast, and Savannah regions. The transgenic PBRC variety, Songotra-T (Sampea 2010-T), was tested against two commercial varieties (Kirkhouse and Wankae) as well as its non-transgenic sister line Songotra.

In Burkina Faso, the trials focused on the Southwest region. Two transgenic PBRC varieties – IT97KT (Sampea 2010-T) and NAFI-T, both introgressed with the Bt gene – were evaluated against the conventional commercial variety TILIGRE. The results showed evidence that in Ghana, the transgenic PBRC outperformed the best commercial variety by 429 percent in the Northern region, 76 percent in the Upper West, 45 percent in the Northeast, and 47 percent in the Savannah. In Burkina Faso's Southwest region, NAFI-T and IT97KT surpassed TILIGRE by 57 percent and 38.2 percent, respectively. These findings provide strong evidence that the transgenic cowpea varieties are highly effective against the cowpea pod borer and offer significant yield advantages in areas heavily affected by the pest, such as northern Ghana and southwestern Burkina Faso.

Partners:

- Council for Savannah Industrial Research/Savannah Agricultural Research Institute, Ghana
- National Biosafety Authority, Ghana
- Institut de l'Environnement et des Recherches Agricoles (INERA), Burkina Faso.
- Agence Nationale de Biosécurité (ANB), Burkina Faso.
- African Agricultural Technology Foundation (AATF).
- Institut de l'Environnement et des Recherches Agricoles (INERA), Burkina Faso.
- Agence Nationale de Biosécurité (ANB), Burkina Faso.
- African Agricultural Technology Foundation (AATF).

TABLE 4.1—RESEARCH ON GENETIC ENGINEERING AND GENOME EDITING IN AFRICA

Crops	GEd (traits/country)	GEn (traits/country)
Cassava	Cassava bacterial blight - Nigeria	Cassava brown streak virus – Kenya, Uganda, Rwanda
	SACMV – South Africa	
Potato	Potato virus Y – South Africa	Bacterial blight – Kenya, Ethiopia, Uganda
Banana	Xanthomonas wilt – Kenya,	Xanthomonas wilt – Kenya, Uganda
Rice		Nitrogen use, water use efficiency, and salt tolerance – Ghana, Nigeria, Uganda
Brassica Carinata	Low erucic acid - Ethiopia	
	Glucosinolate - Ethiopia	
Teff	Semi dwarf against lodging- Ethiopia	
Cotton		Insect resistance/herbicide tolerance – Cameroon, Kenya, Sudan, Nigeria
		Salt tolerance - Egypt
Maize	Drought tolerance - Kenya	Drought tolerance – Kenya, Nigeria, Ethiopia, Mozambique, Tanzania, Uganda
	Maize Lethal Necrosis	Insect resistance, FAW, Stem borer - Kenya, Nigeria, Ethiopia, Mozambique, Tanzania, Uganda
Sorghum	Striga resistance – Kenya, Ethiopia	Biofortified -vit E. A, carotenoids – Nigeria, Kenya, Burkina Faso, South Africa, Egypt
Cowpea		Maruca resistance – Nigeria, Ghana, Burkina Faso, Malawi
Sugarcane		Crop composition – South Africa
Wheat		Drought tolerance, fungus resistance, salt tolerance

excessive flooding (leading to crop submergence). Through gene discovery studies using markers, the International Rice Research Institute (IRRI) identified genes that were used to develop submergence-tolerant rice both in Asia and Africa, thereby increasing yields in flood-prone areas (Anumalla et al. 2025).

Addressing malnutrition

Malnutrition remains a critical issue in Africa, affecting millions and leading to numerous health and socio-economic disparities (Owolade et al. 2022). To address this crisis, innovative approaches that ensure long-term nutritional security are essential. One promising solution is genetic biofortification (GB), which enhances the nutritional content of staple crops through conventional plant breeding and agricultural biotechnology (Kiran et al. 2022). This approach involves identifying genes that code for essential nutrient traits and incorporating them into crop varieties using genetic engineering or traditional breeding methods. Gene editing for nutrition improvement has been done in many crops for diverse traits such as β-carotene content in rice (Fiaz et al. 2021), for Zn in wheat, and for vitamin E in barley (Gupta et al. 2022). Through biotechnology, efforts to improve human health have led to a better understanding of plant metabolism, enabling the enhancement of nutrients such as iron and vitamins A, B9, C, and E (Narayanan 2019). Genetic engineering has also been used to improve micronutrients in crops, resulting in biofortified crops with increased levels of vital nutrients such as folate, iron, zinc, and vitamin A (Mmbando and Missanga 2024). For example, the technique has been used to improve vitamin A in East African bananas.

Additional measures will need to be taken to complement the development of nutrient-rich crops facilitated by biotechnology. For example, African governments will need to promote the concept of Nutrition Sensitive Agriculture (NSA) as part of efforts to address malnutrition. The development of nutrient-rich crops is rapidly improving farmers' access to such varieties and promoting greater consumption through awareness efforts. However, some argue that undernutrition in Africa is primarily a result of poverty. Under the nutrition-sensitive agriculture (NSA) strategy, increased income from non-nutritive crops – whose productivity has been enhanced through biotechnology – is strengthening smallholder farmers' purchasing power and enabling them to better meet their nutritional needs.

Strategic molecular breeding applications for optimizing opportunities in agriculture

Classical plant breeding has driven advances in crop improvement for decades, with improved yields, but the classical approach is relatively inefficient and less precise, with long delays in the product development process and a slow pace of genetic gain. Molecular breeding approaches have facilitated advances in knowledge and a better understanding of genetic traits and their effective manipulation in breeding programs (Krishna et al. 2023).

Gene discovery and molecular markers

Gene discovery was initially supported by the use of molecular markers, which helped tag specific traits and track them in breeding programs through marker-assisted selection (MAS). This approach was particularly effective for simple traits controlled by a few major or dominant genes, characterized by oligogenic inheritance across populations and generations. However, the initial paucity of markers (Grover and Sharma 2016) did not help to translate the power of molecular genetics as rapidly as was hoped, especially as most of the traits driving food and nutrition security are driven by several genes (polygenic). These are complex traits that are difficult to manipulate through breeding and often have limited impact, highlighting the importance of robust designs and strategies supported by appropriate biotechnology tools and techniques to drive successful product development.

The discovery of single nucleotide polymorphism (SNP) markers has redefined marker-assisted breeding, exemplified by approaches such as marker-assisted recurrent selection (MARS), which has significantly improved the breeding of complex traits through the use of novel populations such as multi-parent advanced generation intercross (MAGIC) populations. This also helped the discovery of more useful genes for complex traits, further aiding crop improvement. Building on these advances, genomic selection (GS) has leveraged additive genetic variance to strengthen control over breeding outcomes. Algorithms have been further refined to account for non-additive genes that drive heterosis and superior crop performance, particularly in clonally propagated crops such as cassava, where these traits can be easily fixed and maintained across successive cropping seasons (Tian and Yu 2019).

The emergence of NextGen sequencing technologies has accelerated the dissection of plant and animal genomes, strengthening the power of molecular breeding to explore genomics to the full, with strong predictive power for trait expression and crop performance (Buch et al. 2023; Kayihan et al. 2023). These advancements have greatly reduced the need for extensive field phenotyping, lowering breeding costs, accelerating product development, and shortening the time required for the release of new varieties. The different molecular breeding techniques that have evolved over time have been innovatively combined to drive genetic gains. For example, the WEMA project applied MARS and genomic selection to develop DroughtTEGO maize varieties, which are now widely distributed across several African countries, including Kenya, Uganda, and South Africa.

Transgenics

Gene cloning and NextGen sequencing have facilitated the targeting of useful genes in plant, animal, and microbial species and their use in breeding across species (Kayihan et al. 2023). Useful genes have been introduced from bacteria for pest tolerance/resistance and climate resilience. For example, the development of TELA transgenic maize, using the Bt gene for protection against stem borer (MON810), fall army worm (MON 89034) and MON87460 for drought tolerance (CspB gene) is a paradigm that explores step-wise and multiple techniques (pedigree breeding, MARS, GS, and genetic engineering) to improve genetic gain (Oyekunle et al. 2023). While concerns are often raised about the potential for transgenic traits to spread to wild plant populations and reduce native biodiversity, environmental risk assessments (addressing issues such as weediness and impacts on non-target species) are mandatory components of GMO regulatory processes and must be carefully monitored.

Transgenic research has gained traction in Africa over the past 20 years; however, only 11 countries (22 percent) have commercially approved GMO products (Mmbando, 2024). A few countries (Nigeria, South Africa, Ghana, and Ethiopia) have released GMOs as food crops. Opportunities are still highly limited for this technology, and under the new CAADP strategy, this constraint must be overcome to unlock the potential of the technology in the development of food systems in Africa.

Gene editing

Among all the new plant breeding techniques facilitated by NextGen, genome editing (GEd) is particularly promising. GEd is a site-directed mutagenesis that permits editing (deletion, insertion, modification) of an organism's DNA at a specific locus/locus of interest. Public acceptance is higher compared to transgenics, as foreign genes are not introduced during product development. The technique has been widely applied, typically targeting a small number of genes (usually six to eight), making it well-suited for oligogenic traits. However, multiplex genome editing that targets entire gene families through crossing schemes has also been shown to improve complex traits such as yield and drought tolerance.

This technique is facilitating new, novel traits for food and nutrition. Through GEd, the nexus between certain traits that were difficult to manipulate due to the inverse relationships involved – between grain number and grain size in sorghum, for example – is now being easily mitigated (Endalamaw et al. 2025). GEd opens up new opportunities to optimize biotechnology applications to quickly improve many crops. Genome editing has been applied to develop more than 50 crops and plant varieties, including Striga-resistant sorghum in Africa. Other products include herbicide-tolerant canola, waxy corn enriched with amylopectin, and Calyx high-oleic soybean. Some of these products have reached commercial markets, though none have yet been released in Africa.

The CRISPR technique is the most popular system for genome editing and is used to deliver novel synthetic loci (based on desirable haplotypes, novel genes, or positive alleles for strategic traits). A key advantage of CRISPR/Cas9 is the opportunity it provides to simultaneously edit multiple target genes. Some of its limitations include unintended mutations and challenges in achieving complex genome modifications. For example, targeted alleles could carry additional modifications (such as deletion, partial or multiple integration of the targeting vector, and perhaps duplications), and unwanted events at the target locus. Key areas for further improving this tool include achieving simultaneous multi-gene targeting, increasing the frequency and reliability of multiple edits, minimizing or eliminating off-types, developing transgene-free products, and reducing genotype specificity, with or without reliance on tissue culture.

The art of molecular breeding: designs and paradigms

While genotyping has advanced very fast, improved phenotyping platforms are also needed to optimize molecular breeding. Connecting genotypes efficiently to phenotypes (expression of the genetic instructions) is a major factor that can bring speed to variety development. This minimizes long field trials once trait expressions (phenotypes) can be predicted with precision, with few field trials required to validate performance. Africa will need to invest in a phenotyping platform to boost its molecular breeding capacity. However, several improved varieties with good yield potential have low adoption rates (Akpojotor et al. 2025) among farmers on the continent. A major contributing factor is that many of the key traits underlying preferred food and nutrition qualities in Africa remain poorly understood, both in their genetic makeup and in the biological mechanisms that determine their attributes. Africa needs to develop efficient phenomic platforms for dissecting and understanding these key traits and the underlying genes. Doing so will help with the efficient breeding of improved varieties that satisfy African market demand. Modern phenomic platforms will enable the exploration of advanced tools such as imaging (non-destructive), robotics, and sensors to efficiently relate gene expression to trait response.

Climate change is redefining environments and agroecologies, making crop performance prediction more complicated and challenging. Nevertheless, the ability to accurately determine plant performance or genetic gain on the field through genotyping is the most compelling attraction of modern breeding strategies (Sathvara et al. 2024). Artificial intelligence (AI) is rapidly evolving and is now being integrated to improve crop performance prediction with greater power and precision and to effectively capture climate change variables through a computation process (Pimenow et al. 2024).

Breeding data (from genomics, phenomics, and enviromics), phenotyping infrastructure, and AI have rapidly facilitated paradigm shifts in purposeful breeding, which is critical to accelerating genetic gains and closing yield gaps in Africa. Supported by these drivers (breeding data, phenotyping infrastructure, and AI), several programs now exist to enhance breeding for complex traits. Programs such as smart, predictive, and speed breeding (Xu et al. 2022) will need to be replicated in Africa to accelerate productivity gains. To achieve this, Africa must build capacity in artificial intelligence (AI) and integrate it into biotechnology applications to drive food systems transformation. The complementary deployment of transgene technologies using plant materials developed through genomics is also helping to close the yield gaps in Africa. For example, the HB4 gene has been used to improve drought tolerance in wheat and soybean globally with significant yield increases.

Although transgenic biotech products are seen as controversial, their cultivation is expanding across the globe, and since 1996, when the first one was commercialized, there has been no evidence that they pose any health risk or environmental impact if well deployed (Noack et al. 2024). The public perception of GEd is more favorable, as it involves the development of novel traits without necessarily using foreign genes. Key strategic considerations for deploying genome editing as a precision breeding technique include its use to enhance trait expression, improve heritability, develop industrial and economic traits, discover rare or recessive traits – particularly those related to nutrition and health – and reduce or eliminate deleterious genes to lower genetic load. The tendency to see GEd as an alternative technique to transgenic (GEn) is not correct. However, the ability to explore both GEd and traditional transgenic techniques may offer valuable opportunities to develop synthetic loci that could aid superior crop performance that adequately addresses food, nutrition, and industrial needs (Endalamaw et al. 2025). Such ideotypes are crucial in facilitating enhanced market access for farmers.

One of the key challenges identified with modern breeding is the use of elite lines that have limited genetic diversity, often driven by the need to avoid genetic load and a desire on the part of breeders to accelerate genetic gain. However, pangenome analysis (Wang et al. 2023) has enabled the identification of useful allelic variants through sequencing, which can be harnessed to generate greater genetic variation at key loci and strengthen the resilience of food systems in Africa.

The ability to efficiently deliver the benefits of biotechnology to farmers ultimately depends on delivering good-quality biotech seeds. About 90 percent of Africa's seed system is largely informal (Sperling and Almekinders 2023). Unfortunately, most of the seeds developed through biotechnology cannot be effectively supported by the informal seed system, given the stewardship requirements involved in quality assurance and trait presence. Therefore, Africa must develop its own seed systems as a cornerstone of effective biotechnology application and sustainable agricultural advancement. Research in biotechnology applications for seed systems development is rapidly advancing for early generation seed production. For example, under the Seed Production Technology Africa project, a seed production technology (SPT) using the Ms44 gene is being used to facilitate hybrid seed production in maize. SPT eliminates detasseling and does not allow the development of pollen in a female parent, thus making hybrid production more reliable, efficient, and cost-effective. The SPT utilizes a transgenic maintainer line that is not present in the hybrid produced.

Non-breeding applications

Biotechnology also has wide-ranging applications across human, plant, and animal health, as well as in plant nutrition, disease diagnostics, agro-industrial processes, and environmental remediation. These include:

Biofertilizers

Biofertilizers facilitate the release of nutrients through fixing and solubilization in plants, improvement to soil structure, and greater microbial diversity (Kumar et al. 2022). Genetic engineering and metagenomics have been used to enhance the efficiency of microbial organisms to improve their nutrient-fixing capabilities, efficiency, resilience to environmental stressors, production of hormones for root growth, soil mineralization, and compatibility with diverse crops and soil types. Some of the microbial strains often used as biofertilizers include Rhizobium, Azobacter, Azosprillon, Mycorrhia fungi, and Cyanobacteria. The utilization of these biofertilizers is being enhanced by nanotechnology to control nutrient release. Biofertilizers are expected to become more widely used in preference to synthetic chemical fertilizers, which cause severe damage to the soil, environmental pollution, and contribute to greenhouse gas emissions that are principally responsible for climate change. Biofertilizers are widely used in Asia and Europe. Their use in Africa is growing, but this will need to be intensified to improve soil fertility.

Biopesticides

The threat posed to humans and the environment by synthetic pesticides has necessitated stronger regulatory controls, with the withdrawal of some products from the market. In the US, plant-incorporated protectants (PIP) – pesticidal substances produced by plants from genetic engineering, such as the Bt gene – are considered biopesticides. In Europe, however, PIPs are considered to be biological control agents rather than biopesticides. Microbial (fungi, viruses, bacteria) and botanical/biochemical biopesticides are being improved through genetic engineering and gene editing to enhance their efficacy in controlling biotic stresses in agriculture. Nano biotechnology and micro-encapsulation are being used to enhance their stability and delivery efficacy. Biopesticides are being used to control the fall armyworm in Africa (Kumar et al. 2022).

Health innovations

Biotechnology holds immense promise for revolutionizing human, plant, and animal health across Africa, offering opportunities to enhance the development of affordable and accessible novel diagnostics, therapeutics, and preventive strategies tailored to the specific needs of the continent, especially in the agriculture sector (Singh et al. 2024). Leveraging such modern genetic technologies is particularly crucial in Africa, making strong biosafety management systems essential to minimize potential risks. Overall, the success of such efforts will require deliberate investments in research and development to not only accelerate the adoption of technologies for improving population health but also for fostering socio-economic resilience.

Vaccine production is one example. Despite Africa being the recipient of approximately 25 percent of global vaccine production, the continent is heavily reliant on imported vaccines, with 99 percent of its supply originating from international sources (Sinumvayo et al. 2024). The COVID-19 pandemic demonstrated the power of biotechnology in rapidly producing safe and effective vaccines (Pêgo et al. 2024). The speed and scalability of vaccine production are particularly relevant in the African context, where rapid response capabilities are essential for controlling disease outbreaks such as Ebola, Zika, and other emerging pathogens (Matarazzo and Bettencourt 2023) that continued to affect and disrupt agricultural value chains during the COVID-19 pandemic (Whitley et al. 2022). As such, developing Africa's vaccine-manufacturing capabilities will not only help the continent to cope with future unexpected crises, but will also enable countries to improve the provision of existing vaccines (see Box 4.3 on CRISPR for the African swine fever vaccine, and Box 4.4 on the value of vaccination in livestock).

Affordable therapeutics is another promising area. Biopharmaceuticals, derived from living organisms or their components, present a paradigm shift from traditional chemically synthesized drugs. This enables the development of cost-effective, targeted, and personalized therapies with enhanced efficacy and reduced side effects, capable of managing chronic and infectious diseases that plague animals and humans. The biopharmaceutical industry has witnessed substantial growth over the past three decades, with an increasing number of approved products (such as monoclonal antibodies and recombinant protein vaccines) capturing a significant share of the pharmaceutical market (Kinch et al. 2023). However, the high cost of biopharmaceutical development and manufacturing remains a major barrier to accessibility, especially in low- and middle-income countries. This is where advancements in bioprocessing, formulation, and delivery technologies are crucial in reducing the overall cost of biopharmaceutical production. Innovative bioprocessing techniques, such as continuous manufacturing and single-use bioreactors, can enhance productivity, reduce waste, and lower capital expenditures (Cameron 2021).

Disease diagnostics: molecular tools enable early detection of diseases

Biotechnology, with its innovative molecular tools, offers a transformative approach to disease diagnostics in Africa, enabling the rapid identification of disease-causing pathogens or specific genetic markers with unprecedented sensitivity and specificity, which is crucial for effective treatment and disease control in plants, animals, and humans (Anyanwu et al. 2024). Biotechnology has greatly advanced diagnostic capabilities, enabling rapid interventions in situations that might otherwise have caused severe damage. PCR-based markers have been widely used to detect emerging pathogen strains. With the strong diagnostic power biotechnology provides, plant and animal germplasm have been safely

BOX 4.3—CRISPR FOR AFRICAN SWINE FEVER VACCINE (ILRI, KENYA)

The International Livestock Research Institute (ILRI) in Nairobi, Kenya, is leveraging CRISPR/Cas9 genome editing to develop a live-attenuated vaccine for African Swine Fever (ASF) (Abkallo and Steinaa 2024) , a deadly viral disease with no existing cure (Abkallo et al. 2021). ASF causes near-100 percent mortality in pigs, devastating livelihoods across Africa and globally (Fuchs et al. 2025).

ILRI's team used CRISPR to delete the A238L virulence gene in the ASF virus (ASFV) strain prevalent in East Africa. This precise editing creates a weakened virus that triggers immunity without causing disease. The CRISPR approach slashed vaccine development time from 6 months to under 2 months per candidate, enabling rapid testing of 10 strains annually. Trials showed 100 percent protection in pigs against ASFV, with no adverse effects.

Collaborating with the J. Craig Venter Institute and Friedrich-Loeffler-Institut, ILRI integrated synthetic genomics and CRISPR to assemble modified ASFV genomes efficiently. This "reverse genetics" platform bypasses traditional bottlenecks in vaccine research (LaPointe 2025; Patel 2020).

While the vaccine is undergoing regulatory stability testing, challenges remain in scaling production and securing private-sector partnerships. Success could revolutionize livestock disease management, with potential applications for pathogens like *Theileria parva* (causing East Coast fever).

BOX 4.4—THE VALUE OF VACCINATION IN LIVESTOCK

In the annals of contemporary medicine, vaccines stand as titans, offering unparalleled defense against devastating diseases affecting both humans and livestock, dwarfing the efficacy of other medical interventions. Their impact is particularly pronounced in the realm of animal health, where livestock vaccines demonstrate remarkable effectiveness coupled with exceptional affordability, making them indispensable tools for safeguarding livelihoods and ensuring food security.

Consider the case of Newcastle disease, a virulent scourge of poultry that decimates chicken populations across Africa, with outbreaks often resulting in mortality rates as high as 80 percent (Amoia et al. 2021). Yet, a single dose of Newcastle disease vaccine, expertly administered by a trained vaccinator in a rural setting, costs a mere pittance, approximately 1p (2 US cents), a negligible sum compared to the immense protection it confers. This minuscule investment safeguards a bird's ability to lay eggs, produce offspring, and contribute substantially to the nutritional well-being and economic stability of rural households. Similarly, for East Coast Fever, a single injection of the Muguga Cocktail ITM vaccine provides lifelong immunity to a cow, safeguarding the investments of countless livestock keepers, underscoring the profound value proposition inherent in vaccination.

To fully realize the transformative potential of vaccines, the convergence of several critical elements is essential, encompassing the development of effective vaccines and the establishment of viable markets. GALVmed is playing a pivotal role in this endeavor, leveraging donor funding to harness cutting-edge research and development expertise for the creation of vaccines targeting neglected livestock diseases prevalent in the developing world. GALVmed collaborates with manufacturers and distributors to cultivate sustainable vaccine markets, facilitating the widespread availability and accessibility of these life-saving interventions. Vaccination stands as a paradigm of simplicity and sustainability, empowering small-scale livestock producers to safeguard their most valuable assets – their animals –through the application of one of science's most remarkable achievements: the vaccine.

and efficiently exchanged across countries. Conventional diagnostic methods often fall short in resource-limited settings due to their reliance on sophisticated equipment, trained personnel, and well-equipped laboratories. Molecular tools, however, are increasingly being adapted for point-of-care applications, bringing diagnostic capabilities closer to the patient for better health outcomes (The Plos Digital Health Staff 2022; Drain et al. 2014).

Environmental sustainability

Advances in molecular and biotechnology applications can facilitate the harnessing and protection of Africa's ecology and environment, including the use of endemic microorganisms for bioremediation of industrial wastes and other applications to support environmental conservation efforts. Bioremediation leverages the natural ability of organisms to break down or transform harmful substances into less toxic or harmless forms. This approach is often more sustainable and cost-effective than traditional chemical or physical remediation methods that often leave behind a trail of non-biodegradable contaminants. Biotechnological applications such as genetic engineering can be used to develop microorganisms or enzymes with enhanced pollutant-degrading capabilities (Mondal et al. 2022; Sharma et al. 2024). Likewise, there is potential to harness bioremediation in some African countries as a sustainable approach to land and water restoration, complementing existing environmental management and climate adaptation strategies.

Agro-industrial development

Biotechnology can revolutionize industrial and agricultural practices to improve the quantity and quality of products. The global biotechnology market is still evolving and rapidly expanding, and is projected to reach $1.74 trillion in 2025, equivalent to more than half the size of the global automobile industry (estimated at $2.9 trillion in 2025). It is then expected to grow to approximately $5.04 trillion by 2034, representing a compound annual growth rate (CAGR) of 12.5 percent over the forecast period. The global biofertilizer market reached $1,106.4 million in 2022, and was projected to grow at a rate of 14.2 percent to reach $3,124.5 million by the end of 2024 (Joshi and Gauraha 2022; Kumar et al. 2024). Globally, the turnover of the biopesticide industry is approximately $1.8 billion, and the market availability of different types of microbial cultures and inoculants has increased rapidly over the past decade due to improved biotechnological production schemes. In crop production, the economic benefits of growing GM crops have risen sharply, reaching $261.3 billion, while the area planted with GM varieties increased more than tenfold from just 1.9 million hectares in 1996 to 186 million hectares in 2020 (Brookes 2022).

The growth of the biotech market will continue to play a critical role in developing markets and shaping global trade with countries that have a permissible regulatory environment and trade policies likely to benefit from the windfall. Unfortunately, adoption of biotech crops in African countries remains slow, due to a combination of policy, regulatory, and institutional challenges. A recent study on the cost of delayed adoption of Bt maize, Bt cotton, and late blight-resistant potato in Kenya by Kovak et al. (2024) indicated that over a period of 30 years, these crops could generate $467 million in benefits with significant gains in farm productivity and incomes.

Contribution of biotech to food systems resilience

Food systems encompass a complex interplay of factors that collectively drive progress toward zero hunger, improved health, higher incomes, and overall better livelihoods (Mustafa et al., 2020). The growing threat to highly vulnerable ecosystems – driven by poor agricultural practices and climate change – underscores the urgent need for targeted interventions to build resilience in African food systems and ensure a food- and nutrition-secure continent. Population growth in Africa far outstrips food production capacity, and the rising population is placing pressure on fragile ecosystems in which soil is losing its fertility. Biotechnology offers a wide array of opportunities to address or mitigate these threats.

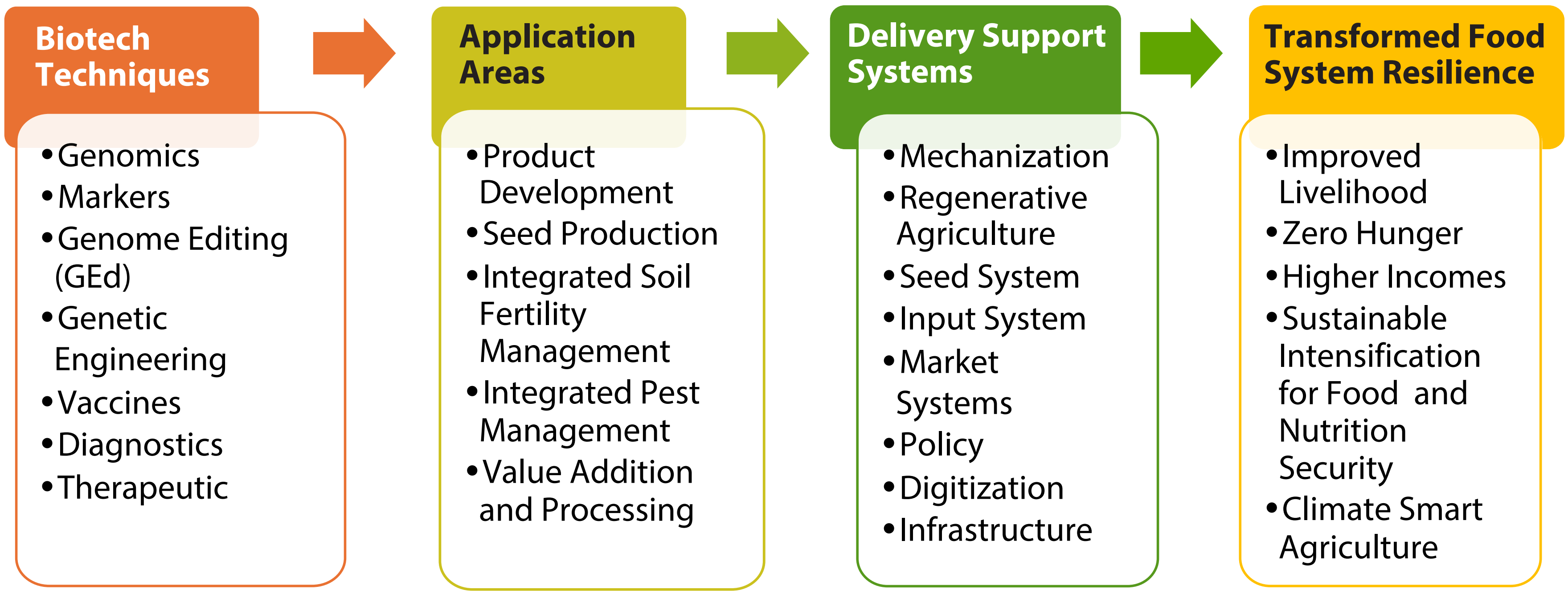
Advances in biotechnology through new breeding techniques (NBTs), bioinformatic analysis, and genotypic and phenotypic platforms have greatly accelerated gene discovery. These tools have helped identify genes related to key traits such as crop adaptation; tolerance and resistance to insects, pathogens, and weeds; yield pathways; drought, heat, and submergence tolerance; carbon sequestration; soil fertility; micronutrient content for human health; and reduced post-harvest losses. These innovative successes have been made possible through an array of biotechnology tools and techniques that have been developed over the years (especially in the last 15 years). For example, a significant share of fresh food is lost to post-harvest deterioration (FAO, 2019). Through biotechnological innovation, value-adding traits are being introduced to enhance product quality, stimulate premium demand, and improve market prices. However, it is important to note that these biotechnology innovations should not be considered a silver bullet for the building of resilient food systems.

Results indicate that, as with improved varieties from conventional breeding, superior varieties with high genetic gain developed through biotechnology have not yet been fully utilized in farmers' fields due to weak deployment strategies within food systems. The potential 'super' products developed through biotechnology have the capacity to support intensive cropping systems, but they must be well deployed if they are to deliver the expected outcomes of a functional and resilient food system (see Figure 4.3). Although numerous biotechnology solutions have been developed, it is not possible to combine all desirable traits into a single product. Therefore, improved varieties should be deployed within a framework that integrates multiple biotechnology solutions alongside complementary production technologies, such as mechanization, to enhance agronomic performance and resource-use efficiency, maximizing the overall benefits of biotechnology. When these biotechnology products are deployed in production systems integrated with digital technologies (e.g., for weather predictions, monitoring for surveillance), field management can be enhanced to improve food systems resilience.

Biotechnology applications are enhancing the integration of pest control, soil fertility, and post-harvest management. However, they must be combined in an efficient way to enhance productivity while supporting ecosystem protection for sustainability. For example, bioengineered soil microbes and phyto-microbes have enhanced soil fertility and nutrient availability, making it possible to minimize the use of inorganic or synthetic fertilizers that increase greenhouse gas emissions and also alter pH conditions with effects on the microbial constitution of the soil (Rebello et al. 2021). Similarly, the control of pests through the use of Bt, in tandem with the use of biopesticides, also offers sustainable ecosystem protection from very toxic pesticides and reduced exposure of farmers to such chemicals (Gul and Beedu 2023). The injection of diverse traits is another huge, beneficial opportunity for food systems resilience. Most of the biotech applications, unfortunately, have been targeted mainly at staples, to the exclusion of other underfunded crops that are important to food and nutrition security in Africa. In effect, some crops in food systems are better protected than others.

It must be stressed that while biotechnology solutions have the potential to transform food systems in Africa, they must be used in a framework of other

FIGURE 4.3—CONTRIBUTION OF BIOTECH INNOVATIONS TO FOOD SYSTEM TRANSFORMATION



complementary efficient systems (inputs, markets, and seed systems) to ensure these innovative solutions are available, easily accessed, and well utilized by farmers for production (Muthie 2021). The other key factor is that biotechnology products need to be applicable to existing farmer production systems in Africa, including regenerative agriculture.

The creation of a favorable enabling environment will be vital to ensuring that biotechnology is fully developed and taken up by users. Robust investment is required to strengthen capacity development and research in biotechnology for more home-grown solutions to meet Africa's needs. Biotechnology is rapidly evolving, and so must the regulatory frameworks to ensure that gaps are not created around the application of promising techniques. Good policy and strong political goodwill are required to foster public-private partnerships, stronger public awareness, and acceptance of biotechnology in Africa. The strengthening of food systems resilience in Africa will largely depend on how quickly the continent's leadership can create an effective enabling environment for agricultural biotechnology development.

The short- and long-term focus for biotechnology application delivery in Africa

Collaborative partnerships between advanced research centers/development agencies and African national agricultural research systems (NARS) have been effective in fostering the biotechnology development process in Africa. In its early stages, research and development (R&D) in biotechnology largely focused on developing human capacity and transferring first-generation biotechnology tools to national agricultural research systems (NARS). Early tools such as tissue culture and molecular markers were deployed and adopted, but on a limited scale due to inadequate funding. This is a challenge that persists today, hindering the wider application and impact of biotechnology innovations. Expertise now exists

TABLE 4.2—SHORT AND LONG-TERM TARGETS FOR AFRICA IN THE DELIVERY OF BIOTECHNOLOGY TECHNIQUES

Techniques	Target	Time Frame	Cost
Tissue culture	Invitro conservation Double haploid Invitro propagation	Short - medium	Low – Medium
Hybridization	SPTA Male sterility	Medium	Medium
Markers and genomics	MAS	Short - medium	Low
	MARS GWAS Genomic selection	Medium	Medium
NPBTS	Transgenic GMOs	Long	High
	Non-transgenic GEd	Medium – Long term	Medium
Biofertilizers Vaccine development Therapeutics Biopesticides		Short- Medium	Low- Medium
Disease diagnostics		Short	Low

on the continent, and this manpower must be properly harnessed to tackle food insecurity through biotechnology. It is likewise important that biotechnology applications are properly classified (as short, medium, and long-term), prioritized, and well-targeted to deliver biotechnology benefits for African farmers.

In Africa, tissue culture has primarily been used to transfer germplasm and eliminate viruses and pathogens from plant varieties, improving the quality and distribution of planting materials to farmers. This short-term biotechnology application can be rapidly scaled up, particularly for clonally propagated crops. However, these crops often have low multiplication rates, making it challenging to produce and distribute sufficient quantities of improved planting materials to farmers within a short timeframe. Closely associated with tissue culture technologies, the semi-autotrophic hydroponics (SAH) is gaining traction in Africa for cassava, yam, potato, and pineapple. This high-propagation technology significantly enhances the capacity to multiply planting materials rapidly and at scale, offering a powerful tool for expanding access to improved varieties (Kulus & Tymoszuk, 2024). (See Box 4.5 on Semi-Autotrophic Hydroponics (SAH): a biotechnology innovation for cassava multiplication).

Another important area is the use of double haploid technology in maize breeding, which enables the rapid development of inbred lines and hybrids. Although it offers strong short-term potential in Africa, its adoption has so far been limited within NARS. Hybrid technology has already revolutionized maize yields in the US.

Several marker-assisted selection (MAS) applications that use a limited number of markers offer valuable opportunities for short-term breeding goals. Numerous mapping populations based on African germplasm already exist in regional research institutions and have been instrumental in identifying quantitative trait loci (QTLs) (Oikeh, 2023). Such QTLs have now been retagged by SNP markers that are enhancing their application because they are robust, abundant, feasible for automated high throughput genotyping, efficient, cost-effective and reproducible (Grover and Sharma 2016). Several SNPs are now available and have been used in breeding programs at NARs. They do not require much investment for further use and can be applied with little funding. Molecular markers and genomic tools have been applied as marker-assisted recurrent selection (MARS), genome-wide association (GWAS), and genomic selection. Through international partnerships, African NARS are gaining access to genotyping-by-sequencing (GBS) tools. These technologies will be more suitable for short- to medium-term targets.

New plant breeding techniques, such as GMO and genome editing, have the potential to revolutionize food systems in Africa, but the opportunities they present are relevant to medium and long-term goals. For example, they provide a means to improve the heritability of traits due to the precision they facilitate in crop improvement. The lack of regulatory frameworks in many countries makes transgenic GMOs a long-term target for Africa. Where genome editing does not involve foreign genes, it will be more desirable as a medium-term technology, although the majority of countries do not have guidelines for this technology yet, and could make this a long-term technology. Facilitating an enabling environment will be an immediate priority for governments and stakeholders.

The costs associated with biotechnology have plummeted as advances have been made in the development of tools. This reduction in costs improves

BOX 4.5—SEMI-AUTOTROPHIC HYDROPONICS FOR CASSAVA MULTIPLICATION

Cassava is a staple for millions of people in Africa, but traditional propagation through stem cuttings or tissue culture is slow, costly, and prone to pests and diseases. This limits the rapid deployment of improved varieties.

Semi-Autotrophic Hydroponics (SAH) is a biotechnology innovation that applies plant tissue culture principles to accelerate cassava seed multiplication. By growing plantlets in controlled trays with optimized substrate, limited water, and reduced exposure to pests and diseases, SAH produces large volumes of clean, high-quality planting material at low cost.

A 40 m^2 SAH setup costs about $10,000, with operating costs of only $0.05 per plant. The method achieves rapid multiplication, high survival rates, and strong returns on investment—80 percent within one year and 116 percent in three years. As well as being affordable, SAH plantlets are more resilient and adaptable to diverse agro ecologies.

SAH has been successfully established in Nigeria, DRC, Tanzania, Rwanda, Malawi, Zambia, Liberia, Kenya, and Angola. In Rwanda, survival rates during acclimatization have reached nearly 100 percent, while in Nigeria and Kenya, private sector and research institutes are scaling the technology to expand seed systems.

By pairing SAH with improved cassava varieties such as disease-resistant, high-dry-matter, or biofortified vitamin A cassava, countries can accelerate adoption, improve food security, and strengthen farmer livelihoods. This makes SAH a proven biotechnology tool for transforming cassava seed systems. Its scalability, affordability, and adaptability make it a game-changer in delivering clean, disease-free planting material to millions of farmers across Africa.

prospects for affordability and acceptability by low- and medium-income countries (LMICs) in the developing world. Genotyping-by-sequencing (GBS) is a low-cost technology, costing less than $0.0017 per marker. It offers a high-throughput genotyping system and has become an important tool in genomics-assisted breeding (de Ronne et al. 2023). The cost of sequencing a whole genome has dropped from $100 million in 2001 to $500 in 2023. The sequencing industry is now setting its sights on a new goal of $100 per genome (WIPO 2024).

The cost of new plant breeding technologies (NPBTs) associated with GMO development and deployment remains very high, although it has dropped from $136 million in 2012 to $115 million (AgbioInvestor 2022). The regulatory phase is the longest part of the process for GM products and is the most significant component of the total cost involved to get a product into the market (Teel 2000). The cost is much lower for genome-edited crops. The overall cost of getting a product to market is, on average $10.5 million over 5 years (Lassoued et al. 2019). Producing transgenic GM crops through genome editing techniques is still cheaper than traditional transgenic approaches, due to their precision. The high cost attached to transgenic GMOs and the regulatory time involved make it a long-term technique. However, in an African context, strengthening investment in biotechnology will remain strategically important as part of the transformation of food systems. Funding for these techniques may be facilitated on a continent-wide basis with multi-country funding or through economic regional blocks and perhaps in partnership with donor/investor agencies to bridge the current gap in biotechnology application delivery.

The non-breeding applications discussed in this chapter – such as disease diagnostics, therapeutics, vaccine development, biofertilizers, and biopesticides – represent low-hanging fruit that can deliver quick, cost-effective gains in the agricultural sector. These areas fall within the short- and medium-term focus and can be fully leveraged at relatively lower cost compared to NPBTs (see Table 4.2).

Looking ahead

Agricultural productivity in Africa lags significantly behind the global average yield output. The task of creating a food- and nutrition-secure Africa will essentially require addressing the following priority targets: bridging the current yield gaps, strengthening climate-smart agriculture, enhancing adaptation, and overcoming malnutrition. Conventional technologies and tools significantly boosted productivity in the past, particularly during the Green Revolution era. However, they lack the precision needed to effectively meet today's growing demand for food and economic development, especially in the context of rapid population growth worldwide, and in Africa in particular. The world has increasingly integrated biotechnology into agriculture, harnessing precision-based tools and techniques to boost productivity in environmentally sustainable ways, ultimately promoting better health and improved livelihoods across societies. In Asia, Latin America, and North America, agricultural development has been significantly boosted by biotechnology to the extent that many countries in these regions are now net exporters of agricultural products. In Europe, too, agriculture has been empowered by biotechnology. Africa, however, remains a net importer of food with import bills that are currently projected to be over $100 billion by 2035.

Biotechnology tools and techniques, with breeding and non-breeding applications, are gradually but slowly being accessed and deployed in Africa. They are yet to be fully adopted and scaled to the extent that they can drive transformative change in food systems. Advances in next-generation sequencing technologies have produced more powerful and precise biotechnology tools and techniques, whose effectiveness depends on optimized strategies to fully realize their potential. They have the capacity to support the development and transformation of food systems, making them resilient and sustainable. Over time, the cost of biotechnology tools has significantly reduced, enhancing their potential to modernize agriculture in the developing world. Under the new CAADP strategy (2026–2035), Africa aims to harness the potential of biotechnology through greater investment and stronger political commitment. The goal is to implement a coordinated plan to transform food systems in line with the continent's Agenda 2063 aspirations and the UN Sustainable Development Goals, ensuring food, nutrition, and economic security across Africa.

Challenges Facing Biotechnology in Africa

As articulated in the previous sections of this chapter, the opportunities offered by biotechnology tools and products hold enormous promise and potential for Africa. For instance, some biotech applications can raise farmers' yields, reduce excessive use of pesticides and other agro-chemical inputs, increase the nutrient value of basic foods, and contribute to the development of elite crop and livestock breeds adapted to tolerate drought, salinity, and low soil nutrients (Ranjha et al. 2022). However, efforts targeted at harnessing modern biotech applications on the continent have faced wide-ranging challenges, ranging from capacity limitations, restrictive policy and regulatory regimes, lackluster public acceptance, and other socio-economic considerations highlighted below.

Infrastructure and capacity limitations

The advancement of biotechnology in Africa is significantly hampered by inadequate infrastructure and limited capacity, posing substantial obstacles to the continent's potential in harnessing biotechnological innovations across various sectors (Amankwaah et al. 2025). The lack of access to advanced equipment and technologies further exacerbates the problem, limiting the ability of African scientists to compete globally and contribute meaningfully to the field (Ngongalah et al. 2019). Consequently, many talented African scientists often seek opportunities abroad, leading to a brain drain that deprives the continent of its most valuable human capital.

The advancement of science, technology, and innovation in Africa also faces significant impediments due to underdeveloped supply chains and inadequate logistical networks (Amankwaah et al. 2025). A functional supply chain is essential to ensure consistent delivery of reagents, equipment, and other essential materials, all of which are critical for conducting cutting-edge research and development in biotechnology. Moreover, these logistical weaknesses lead to elevated costs, delayed project timelines, and compromised research integrity, thereby undermining the overall competitiveness of African biotechnology on the global stage. For example, weak transportation infrastructure across many African countries makes it difficult to move temperature-sensitive biological materials and equipment efficiently and reliably. Cold chain management, in particular, is a crucial aspect of biotechnology, requiring the maintenance of specific temperature ranges during storage and transportation to preserve the integrity of biological samples, vaccines, and pharmaceuticals (Panigrahi et al. 2024). To fully realize the potential of biotechnology in Africa, it is imperative to invest in strengthening supply chain infrastructure, including cold storage facilities and logistical networks to ensure the seamless flow of materials, equipment, and products from manufacturers to end-users.

Policy and regulatory restrictions

Emerging biotechnological applications admittedly offer immense opportunities for Africa to enhance food security, improve healthcare, drive industrial growth, and address environmental needs. However, efforts to roll out biotech products in African countries over the past two decades have stalled due to the number of challenges associated with national policies and legislation governing biosafety (Gbashi et al. 2021). In formulating national regulatory policy for modern biotechnology, countries often take into consideration both the opportunities presented by the technology and attendant potential risks associated with it. The African continent is made up of countries with diverse political persuasions, trade considerations, and environmental interests, leading to an unstreamlined mosaic of national policy positions and regulatory systems for products of modern biotechnology (Kasera 2024; Nang'ayo et al. 2014). These regulatory systems range from those that can be considered to be permissive to modern technological advances on the one hand, to those that are more precautionary and even prohibitive to the adoption of GM crops on the other hand (Kasera 2024).

Virtually all African countries are signatories to the Cartagena Protocol on Biosafety and thereby exercise a guarded and precautionary approach to ensuring safety during the transfer, handling, and use of new products, with a primary focus on protecting biological diversity (Berhan and Egziabher 2005). As such, many African countries have moved on to domesticate the Protocol via a raft of measures, including legislative, institutional, and/or policy-based strategies. Since public perception of GM technology in many parts of the world is still steeped in controversy, public policy on modern biotechnology, especially GM, in many African states is framed with precautionary overtones. In these circumstances, regulatory regimes have emerged that implicitly assume that all GMOs present high risks unless proven otherwise, an approach that often requires inordinate amounts of information and data to be presented to obtain regulatory clearance. Mmbando and Missanga (2024) have observed that setting regulatory safety standards at such a high threshold is a sure way of keeping GM crops out of developing countries, thereby depriving their farmers of the benefits of such technologies (Brookes and Barfoot 2020; Mockshell et al. 2024).

Public perception and acceptance

Public and societal discourse on biotechnology and genetic modification tends to take on a distinctly multi-faceted nature, which often pits arguments supporting the power and potential of biotechnology to drive positive change on the one hand, against arguments about the potential for unforeseen negative consequences, and ethical concerns on the other (Dessie and Zegeye 2024). This unique confluence of ready arguments for and against the technology can overwhelm non-technical audiences, resulting in sustained public skepticism about GMOs and a heightened risk perception that can affect its acceptance.

According to the provisions of the Cartagena Protocol on Biosafety, which many African countries have signed and ratified, a functional national biosafety framework should contain, among other components, mechanisms for capturing inputs and feedback from the public. This interaction with the public is largely an important demonstration of transparency and fairness in regulatory oversight and goes a long way towards enhancing public confidence in regulatory institutions. A number of national regulatory systems, by law, solicit public views on applications for GM crop trials and release. However, such forums are often dominated by anti-GM lobby groups.

In some cases, opposition to modern biotechnology takes on a highly litigious dimension. Several court cases filed in Nigeria, Ghana, and Kenya[2] between 2017 and 2024 serve to illustrate this point. Arguments and biotechnology covering environmental safety, seed sovereignty (the right to control seed systems), and public health concerns, as well as cultural concerns around food sovereignty (the right to control food choices) (Kasera 2024). Interestingly, where sensational claims around food and environmental safety have been disallowed in courts for want of evidence, litigants introduced procedural arguments that claim that regulatory oversight for GMO crops was either weak or compromised, or that public participation in the process was inadequate (Dessie and Zegeye 2024). The diversity of arguments is of particular interest and points to the multifaceted perceptions around the technical, socio-cultural, economic, and political dimensions of arguments against biotechnology. However, it should be remembered that the problems of hunger and poverty in Africa, and the socio-economic context in which they occur, are very different from the problems experienced in developed countries. It is in those countries that most of the biotechnology debate currently takes place, meaning that the positions and conclusions

2 Superior court of judicature, High Court of Justice, Human Rights Division, Ghana, 24 May 2024. Republic of Kenya, in the Court of Appeal at Nairobi, Civil Application Number E474 of 2022. High Court of Justice of Nigeria, Abuja Judicial Division, August 2017.

emerging from the GMO debate are largely irrelevant for smallholder farmers in many African countries (Diamond et al. 2020).

Funding and investment

Sustained funding for biotechnology research from domestic public resources is essential for long-term progress. However, government support across Africa remains limited, leaving most investments dependent on international donors. This reliance poses risks to the continuity of biotechnology research, as donor priorities can shift over time. More broadly, agricultural research and development in Africa has long been hampered by chronic underinvestment and fluctuating annual funding levels.

According to the United Nations Educational, Scientific, and Cultural Organization (UNESCO), indicators of science, technology, and innovation (STI) show exponential growth in Asia, led by China, reflecting the continent's repositioning as the world's economic powerhouse (Kamba 2024). By contrast, Africa remains at the bottom of global research indicators. According to UNESCO, global R&D expenditure rose from about 1.72 percent of GDP in 2015 to approximately 1.95 percent in 2022, with major increases in regions such as East and South-East Asia and North America, while Africa south of the Sahara has stagnated or declined. Not surprisingly, modern biotechnology applications in Africa have grown much more slowly than in the rest of the world, despite the fact that Africa is disproportionately affected by malnutrition and food insecurity (Mmbando 2025).

Ownership, equity, and access to intellectual property rights

Within the agricultural biotechnology sphere, patents and Plant Breeders' Rights (PBRs) are the key Intellectual Property (IP) assets that one would register to acquire legal ownership. IP broadly refers to the creations of the human mind (Smith 2019). Intellectual Property Rights (IPRs) are created through the enactment of international, regional, and national laws, outlining the rights and obligations of an individual or legal entity (Savale and Savale 2018). These rights are territorial and exclusive in nature, subject to the exemptions outlined in the law.

There has been an increase in the quest for patent and plant variety protection within Africa. However, statistics indicate that Africa is lagging in seeking IPR protection (Ugwu 2022). The World Intellectual Property Indicator for 2024 shows that the leading countries seeking patent protection were China, the US, and Japan, while the leading countries or regions seeking PBRs were China, the EU, and the US (WIPO 2024). Additionally, in a 2020 report by the United Nations Office of the Special Adviser on Africa, the continent accounted for only 0.5 percent of the world's patent applications, compared to 66.6 percent for Asia, 19.3 percent for North America, and 10.9 percent for Europe (Zhou 2019). These figures clearly indicate that ownership of agricultural biotechnology products is mostly situated outside of Africa, making access to those products an area of concern.

As these inventions are developed mostly by private sector companies in Western countries, access to biotechnology products by African seed companies is achieved through complex licensing agreements (WIPO 2024). These licenses, whether exclusive, sole, or non-exclusive, come with royalty fees to be paid to the product owner. Smallholder farmers, therefore, struggle to purchase IP-protected biotechnology products, as the royalties charged make them relatively expensive in comparison to other similar products on the market (Chaturvedi 2015). While small-scale farmers argue that the product is relatively expensive, the developer ascertains that the royalty charged is to recoup the investment made during the research and development phase. The complexity of access, costs, and licensing technicalities hinders access to biotech products by researchers, seed companies, and smallholder farmers, creating what some see as a conflict between intellectual property rights and the rights of farmers in developing countries (Shand 1991).

These challenges call for equitable partnership between public and private sector entities. Through collaboration, practical solutions could be identified and implemented to ensure the enhanced promotion of IPR protection by African researchers while supporting smallholder farmers to gain access to these technologies (Kuyek 2002). The TELA project – now known as Biotech Maize Seed Systems (BMSS) – and the Pod Borer Resistant (PBR) Cowpea projects are key examples of such partnerships. Both projects are coordinated by the African Agricultural Technology Foundation (AATF), which brings together national agricultural research institutions, germplasm developers, and seed companies to collaborate and deploy elite agricultural biotechnology products to farmers in Africa south of the Sahara (Oikeh 2023). Through these partnerships, AATF licenses agricultural biotechnology from third parties and then sublicenses these technologies royalty-free to seed companies on humanitarian grounds.

Biotechnology product stewardship

It is evident that agricultural biotechnology offers promising tools to address the critical challenges of ensuring agricultural food systems sustainability in Africa by enhancing crop yields, improving nutritional content, and increasing resistance to pests and diseases. However, successful and sustainable deployment of agricultural biotechnology products requires robust stewardship practices that safeguard product integrity and durability (Walter et al. 2018). In the context of African agriculture, this presents a complex web of challenges, stemming from a combination of biological, regulatory, socioeconomic, and infrastructural limitations. For instance, quality assurance requirements such as assessing the genetic purity and trait stability of genetically modified seeds require specialized techniques and expertise that are not often readily available in many African countries. Standardized protocols and quality control measures are often absent, which further exacerbates the problem, leading to inconsistencies in seed quality and hindering efforts to ensure that farmers receive seeds that meet the required standards. Furthermore, the cost of quality assurance measures, such as seed certification and labeling, can be prohibitive for small-scale seed producers and distributors, hindering their ability to participate in the formal seed sector. The absence of well-established extension services and farmer education programs exacerbates this issue, leaving farmers vulnerable to misinformation and potentially leading to the misuse of biotechnology products.

Policy and Regulatory Proposals for Harnessing Biotechnology in Africa

Despite noticeable progress in biotechnology research, a combination of technical and political challenges continues to hamper the adoption and deployment of biotech applications in Africa. Although nearly 1.5 billion people on the continent rely on agriculture, investment in biotechnology is marginal compared to other parts of the world. Governments prioritize politically safe inputs and infrastructure, leaving biotech dependent on donors. Limited R&D spending hampers progress, with Egypt being the only notable investor in biotechnology. Greater domestic investment is needed in order to meet CAADP targets. This section proposes a suite of policy, regulatory, and institutional recommendations that promote the advancement of modern biotechnology across the continent.

Strengthening biosafety regulations

While weighing the potential benefits and risks that biotechnology presents for Africa, policymakers should focus on facilitating access to innovative biotechnology products by establishing a functional and enabling regulatory environment. Policy approaches need to promote responsible regulation of innovative biotechnology products, balancing the optimization of their benefits with robust safeguards for public and environmental health. Currently, only 13 countries in Africa have established the biotechnology regulations that are needed to drive the development, deployment, and commercialization of biotech products. These countries have also established some level of biotechnology research capacity, but progress is still slow due to fragmented regulatory frameworks, funding constraints, and public skepticism (Trump et al., 2023). However, while establishing regulations is necessary, this alone will not ensure the successful adoption and implementation of biotechnology. Making policies functional through effective implementation will yield better outcomes.

Accelerating regional harmonization

Policymaking tends to be country-centric, with scant consideration of regional trade or the cross-border movement of agricultural goods. This results in a patchwork of regulatory approaches from one country to another, ranging from permissive to precautionary, which disrupts trade and delays innovation (Stojčić et al. 2025). The absence of policy coherence undermines the development goals articulated in Agenda 2063, particularly the agricultural priorities set forth in the CAADP Malabo Policy framework (AUC and AUDA-NEPAD 2024) that primarily sought to boost intra-African trade in line with the African Continental Free Trade Area (AfCFTA) Agreement.

Regional harmonization through platforms such as COMESA, the East African Community (EAC), and ECOWAS can streamline biotech approvals, reduce duplication, and strengthen cross-border collaboration (ISAAA 2015). Institutions like the African Biosafety Network of Expertise (ABNE) should be equipped to support regulatory development and training (NEPAD 2022). Efforts to achieve regional harmonization are slowly gaining traction across

Africa: COMESA initiated consultative engagements on harmonization over 15 years ago, culminating in the approval of the Harmonized Policy on Modern Biotechnology in 2016 and the launch of the COMESA Biotechnology Implementation Plan (COMBIP) in 2017. ECOWAS and the West African Economic and Monetary Union have initiated similar efforts, though implementation remains limited (ISAAA 2015). Although COMESA and ECOWAS adopted harmonized seed regulations in 2008 and 2014, respectively, an integrated regional seed market has yet to materialize, highlighting the gap between policy adoption and implementation.

Enhancing public investment in biotechnology

Public investment in biotechnology is increasingly recognized as a priority due to its potential for economic growth, national security, and addressing global challenges. Effective biotech development depends on physical and institutional infrastructure, including laboratories, storage systems, and testing facilities. Studies highlight the need for significant investment in genomics facilities, cold chains, and seed processing centers (Thatoi et al. 2025). Governments worldwide are establishing strategies, funding research, and fostering collaborations to unlock the full potential of this rapidly evolving field. However, breakthroughs in biotechnology will require adequate public investment in critical R&D. Agricultural spending overall represents just 4 percent of total government expenditure in most countries in Africa south of the Sahara, indicating limited prioritization of agricultural innovation in public policy (Dante Israel Leon-De La et al. 2018).

Incentivizing private-sector investment in biotechnology

Incentivizing the private sector through public policy can drive private investment in biotechnology. One model that has yielded results is large-scale investment from venture capital (VC) firms . In Italy, the growth and success of the biotechnology sector has been attributed to VC, with all evidence indicating that the amalgam of VC and biotech companies sums up to more than its constituent parts. A collaborative model can yield even larger benefits, with governments playing the role of financing research and development of the knowledge base while the private sector focuses on developing commercial products and markets. Alliances between firms have also succeeded in driving the commercialization of biotechnology innovations (Thomson 2015). In the US, for example, co-financing mechanisms where large firms supplement in-house R&D by acquiring research products and/or new technologies from small firms as well as universities have led to substantial outcomes. Public-Private Partnerships (PPPs) are also a viable model for financing biotech investments. A case in point is the WEMA-TELA Project partnership led by AATF: this is a consortium of NARS institutions, seed companies, and the Consultative Group on International Agricultural Research (CGIAR) centers to deliver climate-smart, insect-resistant maize hybrids to smallholder farmers in Africa (Muthie 2021).

Building public trust through inclusive engagement and communication

Public skepticism, often driven by misinformation, continues to hinder the adoption of agricultural biotechnology in Africa. Mistrust stems from cultural concerns, limited awareness, and fears over environmental and health risks (Sadikiel Mmbando 2024). Addressing this requires inclusive stakeholder engagement throughout the research and development process to ensure local needs and values are reflected. Involving farmers, community leaders, civil society, and policymakers fosters legitimacy and trust. Evidence from countries such as Burkina Faso and Nigeria shows that transparent, participatory processes improve technology acceptance (Kovak et al., 2024). Effective communication strategies may include trusted channels and community voices that are instrumental in countering misinformation and shaping public perception. Integrating biotechnology into education systems also builds long-term understanding. Highlighting socio-economic benefits such as yield gains and input cost reduction through real-life success stories can further reinforce public confidence. Continuous public dialogue, including forums and participatory assessments, can enhance transparency and responsiveness from institutions (Komen et al. 2014).

Conclusion

Rapid population growth in Africa continues to exert immense pressure on existing food systems, straining resources and exacerbating food insecurity, particularly in rural areas. The adoption of system-level approaches to building resilient and sustainable food systems on the continent is therefore an imperative. Africa must modernize its agriculture by embracing solutions and strategic innovations to drive change in the sector in line with the Agenda 2063 aspirations and UN strategic development goals.

Biotechnology presents a transformative opportunity for Africa to address pressing challenges in food and nutrition security, climate resilience, and sustainable agricultural productivity. As outlined in this chapter, Africa's rich biodiversity, diverse agroecologies, and fledgling scientific capabilities position it to benefit from a broad suite of biotechnological applications: from genetic engineering and genome editing to biofertilizers and diagnostics. For instance, the few African countries that have adopted GM crops have witnessed significant yield and income increases. In South Africa, the introduction of GM maize, soybean, and cotton helped raise farmers' incomes by more than $1 billion between 1998 and 2012. Overall, the adoption of GM crop varieties in South Africa increased annual crop yields by 32 percent. Elsewhere, Nigeria's farmers now grow GM maize and GM cowpea – varieties that have been improved to resist infestation and destruction by insect pests, therefore requiring fewer or even no pesticide applications.

However, only 15 countries in Africa have established functional regulatory systems to govern innovative and emerging technologies. On a positive note, over the past 25 years, there has been a steady rise in the number of countries adopting biotech crops: from just three in 2003 to 12 in 2025. The latest entrant is Rwanda, which in only two years has managed to establish a robust regulatory system now governing R&D efforts in GM maize, cassava, and Irish potato.

Since the late 20th century, biotechnology has emerged as the single biggest driver of transformation in the global agricultural landscape. Africa must urgently strengthen its biotechnology capacity to harness the technology's power, speed, and efficiency. By leveraging a combination of biotechnological solutions, the continent can more effectively address its interlinked challenges and build a resilient, food-secure future for its growing population. Fortunately, Africa is endowed with high-quality land and water resources in addition to having strong biodiversity and highly diverse agroecologies, all of which help to support a vast array of crops. Biotechnology has the potential to sustainably drive these resources efficiently for the benefit of the continent. Concerted investments are critical for harnessing the untapped potential of modern biotechnology in Africa. Such investments would enable research systems in Africa to develop home-grown biotechnology solutions owned by Africa for the development of its food systems. However, this requires the development of regulatory systems for modern biotechnology that are harmonized across the continent. African governments, therefore, have a role in providing strong political will and support for biotechnology development. Such support will be crucial to creating an enabling environment for transformative change to food systems.

It is worth underlining that biotechnology solutions have been successfully deployed in the Americas and Asia and, to some extent, in Europe to enhance climate-smart agriculture, improved nutrition for better human health, and ecosystem protection. However, biotechnology is not a silver bullet. The benefits of biotechnology are optimized when deployed in sync with the best production management practices (e.g., integrated pest and soil fertility management, regenerative agriculture, mechanization, etc.) to create multiplier effects for higher investment returns. The deployment of biotechnology solutions in Africa must be contextualized within the development needs of the continent. Productivity (yield), though very important, must not be prioritized over other traditional food values. The failure to factor this need into breeding pipelines has been a major reason for low adoption of improved varieties, and this must be guarded against in molecular breeding. Fortunately, biotechnology offers an opportunity to dissect many key traits.

In conclusion, while biotechnology is not a panacea, it remains an indispensable tool in Africa's quest for sustainable and resilient food systems. The continent's future food security, economic prosperity, and environmental sustainability depend on how effectively it can harness this innovation frontier. For Africa to realize the goals of Agenda 2063 and the Sustainable Development Goals, biotechnology must be mainstreamed into food systems transformation strategies with urgency and deliberate investment. The greatest impact of biotechnology is likely to emerge when integrated with complementary strategies such as regenerative agriculture, mechanization, robust input, and market systems. Building public trust through evidence-based, culturally sensitive communication, along with fostering public-private partnerships, will be vital to the uptake of biotech applications. Three key policy directions are imperative: (1) Increase public investment in biotechnology R&D, aligning with the post-Malabo Agenda and meeting the 10 percent agriculture budget target; (2) Accelerate regionally harmonized regulatory frameworks to reduce costs, facilitate trade, and support innovation; and (3) Ensure responsible, enabling regulations that allow timely access to beneficial biotechnology products while safeguarding public and environmental health.