Original Research Article

Advances in the Use of Genome Editing Tools in Africa: A Review

Abstract

Africa is grappling with various challenges, particularly in agricultural production and disease prevention affecting humans, animals, and crops. Genome editing (GE) technologies, especially CRISPR/Cas9, have emerged as effective tools to tackle these issues. Here, we provided a comprehensive review of how these GE tools have enhanced resilience against biotic and abiotic stresses, leading to increased yields. We elaborated on how GE has also facilitated the development of disease-resistant varieties of bananas, cassava, and maize, effectively addressing plant diseases like cassava mosaic and brown streak by targeting specific genes. We further emphasized the application of GE in animal breeding, exploring the successful creation of disease-resistant livestock and developing vaccines against diseases. Our findings explored the applications of GE in tackling human health challenges, including artemisinin resistance and hepatitis B treatment. Our summary however highlighted limited adoption of the GE technologies only in a few African countries such as Kenya, South Africa, Nigeria, Ethiopia, Egypt, Uganda, Burkina Faso, Ghana and Rwanda. We further reported the persistence of societal issues despite its advancement, including religious beliefs and concerns about the implications of GE in homes, leading to fear and discrimination against its use. We finally reported the efforts of scientists in advocating for policies and consensus on implementing GE in Africa to address these challenges.

Keywords: Genome editing, Africa, Progress, Challenges, Prospects.

1.0 Background of the Study

In most countries, especially in low-income African countries, infectious diseases and food insecurity have hampered economic progress [1]. The world faces three major challenges: increasing agricultural yields despite limited land and water resources, ensuring affordable and accessible planting materials (particularly in Africa), and producing food with enhanced nutritional value [2, 3]. Mennechet and Takoudjou-Dzomo's 2020 report stresses that Africa has the most significant healthcare resource gaps and higher mortality rates due to infectious diseases. To address these issues, African nations should actively implement advanced technologies, such as genome editing, to combat health challenges [4].

Genome editing (GE) alters an organism's DNA at particular genomic sites to alter biological activities [5]. This can be accomplished by knocking down undesirable genes or phenotypes, permanently inserting any foreign DNA, or activating, overexpressing, or silencing genes [6, 7]. Almost every field of human effort has applications for this technology, including industry, agriculture, and medicine, all of which are essential to our way of life and overall health. According to Geller *et al*. [8], GE has enormous potential for developing proactive, effective, and individualized strategies for treating and preventing infectious diseases [8]. Many scientists have used GE techniques to improve and/or create novel traits, such as increased therapeutic possibilities, improved yield potential, stress tolerance, disease resistance, drought resistance, gene therapy, and vaccines [9, 10].

GE technologies include transcription activator-like effector nucleases (TALENs), mega-nucleases, zinc-finger nucleases (ZFN), and clustered regularly interspaced short palindromic repeats (CRISPR)/Cas9 [11]. Mega-nucleases are DNA-splitting enzymes that identify DNA targets up to 20 base pairs long and are encoded by mobile genetic elements, or introns [3]. ZFNs are specifically designed Cys2-His2 zinc-finger protein and the FokI restriction endonuclease cleavage domain, while TALENs are derived from bacterial TALEs and comprise an amino-terminal TALE DNA-binding domain connected to a carboxy-terminal FokI cleavage domain [12, 13]. The *Streptococcus pyogenes* adaptive immune system is the source of CRISPR/Cas9 [3]. Because of its versatility, specificity, adaptability, ease of use, and ability to multiplex traits, CRISPR/Cas9 has become the most used GE technique to date [14]. Once the scientific community realized how easy it was to use CRISPR-Cas tools for gene-editing applications, this method quickly became the standard [14]. It has been demonstrated that CRISPR-Cas tools have many potential applications for large insertions or deletions, INDELs, substitutions, inversions, duplications, and other complex alterations that were challenging to accomplish with conventional approaches [15, 16]. GE techniques have been effectively used to address genetic problems in kids, persistent infertility, and other life-threatening conditions for which there is no other available treatment.

Despite notable progress in the CRISPR guide RNA selection, protein and guide engineering, novel enzymes, and off-target detection methodologies, the Cas9 protein has been found to bind and fragment DNA in non-target areas [17]. Also, important ethical concerns about designer babies, species-specific bioweapons, and invasive mutants have been raised by scientific research on the use of gene editing tools, particularly in the development of novel treatments and the identification of the function(s) of specific genes [18]. Globally, the GE tools have enabled humankind to experience unthinkable levels of development, and African nations shouldn't be excluded. Therefore, by listing the African nations that have embraced the advantages of GE and providing an overview of the latest developments in GE tool application for crops, animals, and genetic disease correction, we hope to shed light on the advancements in GE tool use in Africa. Additionally, this study will explain why genome editing technologies are still considered science fiction in Africa and, lastly, what the future holds.

2.0 Gene editing in the field of Agriculture

2.1 Application of Gene-Editing tools for African crop/plant Improvement

Scientists are developing crops with enhanced nutritional quality, resistance to pests and diseases, tolerance to abiotic stressors, and industrial and pharmaceutical applications using genetic engineering techniques [19, 20]. The following subheadings address the use of GE methods for agricultural enhancement in Africa:

2.1.1 Biotic Stress Resistance

Weeds, diseases, and pests can compromise food safety if left unmanaged and result in large financial losses [21]. An entire crop may be lost, depending on how bad the infestation is. For this reason, a lot of work is being done to create crops that are naturally resistant to biotic stress [19]. Developing disease-resistant bananas is now feasible with the help of CRISPR/Cas9 and other targeted GE technologies. Because of the availability of CRISPR/Cas9 GE techniques and comprehensive banana genome sequences, constructing disease-resistant bananas is achieved by carefully knocking off the endogenous genes [22]. Several susceptibility genes linked to bacterial resistance have been found and targeted for editing in a variety of plants [23]. Research to create genome-edited bananas resistant to bacterial wilt disease is now being conducted at the International Institute of Tropical Africa (IITA) in Kenya [24].

Furthermore, studies have attempted to develop resistance to cassava's two main and severe viral diseases, cassava Mosaic Disease (CMD) and cassava Brown Streak Disease (CBSD), using CRISPR/Cas9 technology [25, 26]. To achieve this, a single gRNA was used to silence the viral AC2 and AC3 genes, which are genes that play great roles in gene activation, virus pathogenicity, repression, and replication enhancement respectively [25, 26]. Mehta *et al*. [26] created cassava lines that were resistant to CMD by engineering transgenic plants to express the Cas9 gene using a guide RNA aimed at targeting the genome of the virus. When tested, the researchers didn't observe the resistance of the plants to CMD under greenhouse conditions. This then led to the whole genome sequencing of the virus and infected wild-type plants, and a variety of mutations occurred within the targeted region of the gRNA, resulting in premature stop codons in the AC2 and AC3 Open Reading Frames [26].

Furthermore, gene editing has successfully created sorghum plants that are resistant to the damaging parasite known as witchweed [27]. Similarly, the CRISPR system has been employed to enhance crops' resistance to various diseases and infections, including downy mildew in spinach, fire blight in apples, greening in oranges, lethal necrosis in maize, powdery mildew in grapevines, and the Yellow Leaf Curl virus in tomatoes [3]. TALENs have also been used to develop resistance against worms and fungi in wheat and almonds, respectively. Additionally, it has been reported that gene editing can reduce fatal necrosis in maize in Africa, leading to increased grain yields and overall maize production [3].

Scientists are developing a strain of maize that is resistant to Maize Lethal Necrosis (MLN) using CRISPR-mediated GE without affecting desirable traits and performance [28]. With the GE methods, the MLN Gene Editing Project aims to modify four superior maize varieties that are resistant to infections [29]. The MLN had reduced maize yields in Kenya with enormous loss in productivity and the abandonment of maize planting by many smallholder farmers [30]. It is possible to develop new MLN-resistant cultivars of maize and increase the resilience of already-existing cultivars by the use of CRISPR editing in maize plants [31]. If CRISPR-edited maize seedlings are successfully field-planted, food security in African countries will be greatly improved in agriculture. GE has focused on modifying, replacing, or regulating genes to develop disease-resistant crops [31].

2.1.2 Abiotic Stress Resistance

Climate change, which causes drought, floods, salinity, and extremely high temperatures, has shown to be one of the environmental issues that scientists are most concerned about recently [32] Farmers profit from plants' ability to withstand abiotic stressors like cold, salt, drought, and nitrogen shortage [32]. Scientists at Kenyatta University's Plant Transformation Laboratory are utilizing CRISPR-Cas9-mediated gene editing to enhance maize lines' resistance to oxidative stress, genotoxicity, and drought. This system has been effective in modifying various species of plants to improve their tolerance to abiotic stressors [33]. The researchers are specifically transforming maize varieties, which are susceptible to these stressors, as a result of changes in the gene to develop more resilient lines [33, 34].

Researchers in Egypt are adapting the CRISPR-Cas9 technology for developing drought-resistant wheat varieties whose oil quality has been enhanced by targeting the SAL1 gene known for its role in improving plants' tolerance to abiotic stress [35]. Additionally, they are working on creating dwarf and semi-dwarf banana varieties, which are more resilient to storm damage and easier to harvest. This is achieved by modifying the gibberellin 20-oxidase 2 (GA20ox2) gene in *Musa acuminata* to disrupt the gibberellin (GA) pathway [3]. Svitashev *et al*. [36] successfully edited genes such as LG1, MS26, MS45, ALS1, and ALS2 in maize with difficulties when converting elite lines, particularly commercial hybrids from Africa. The collaborative efforts of African researchers have resulted in the successful transformation of tropical maize lines, making it possible to directly alter genes in commercial lines [37].

Abiotic stressors like reduced soil fertility, unpredictable weather patterns (including floods and droughts), and high temperatures negatively impact yam production. To mitigate these challenges, it is essential to develop yam varieties that can adapt to various agroecological zones, particularly in low-nutrient soils [38]. Ou *et al*. [39] highlighted that cassava plants enhance the expression of KUP genes under conditions of increased salinity, lower temperatures, and reduced water availability, which in turn improves their nutritional quality. The research on gene function in different crops has revealed that several genes respond differently to abiotic stress [39].

Increased crop yield is the most researched agro-trait, followed by resistance to biotic stresses (like pests and diseases) and abiotic stresses (such as drought, cold, and salinity). These developments address the agronomic and financial challenges farmers face, including pest attacks and environmental stresses [40]. For long, the introduction of traditional breeding pattern have boosted agricultural productivity, however, the rising need for food necessitates more efficient crop development techniques [41].

Global food production must rise rapidly to fulfill the demands of the expanding African population as well as those of the entire world. The developing pipeline focuses on applying technology in institutes, in collaboration with local and international bodies to improve drought and disease resistance in several crops. The table 1 below highlights the application on GE in institutions with their collaborating institutions.

Table 1: Use of GE for Crop Production in African Countries with their Lead Institutions.

Crops	**Trait**	**Lead Institution**	**Partnering Institution**	**References**
Bananas	Virus resistant varieties	International Institute of Tropical Agriculture (IITA), Nairobi, Kenya	Consultative Group of International Agricultural Research (CGIAR)	[42]
Bananas	Bacterial resistance	International Institute of Tropical Agriculture (IITA), Nairobi, Kenya	Consultative Group of International Agricultural Research (CGIAR)	[43]
Maize	Maize lethal necrosis resistance	Corteva Agriscience	Kenya Agricultural and Livestock Research Institute (KALRO) and the International Centre for Maize and Wheat Improvement (CIMMYT)	[44]
Rice	Bacterial leaf blight-resistant rice	Consultative Group of International Agricultural Research (CGIAR)	Tanzania Agricultural Research Institute (TARI)-Uyole Centre, United Republic of Tanzania; International Rice Research Institute, Eastern and Southern Africa Region, Kenya; International Rice Research Institute (IRRI), Africa Regional Office, Kenya	[45]
Rice	Bacterial wilt-resistant rice	AUDA-NEPAD	Agence National de Biosecurité (ANB), in Burkina Faso	[46]
Tef	Lodging resistant	Corteva Agriscience	Danforth Centre and the Ethiopian Institute for Agricultural Research (EIAR)	[47]
Wheat	Drought tolerance	USDA-ARS, Crop Improvement and Genetics Unit, Albany, USA	Department of Genetics, Faculty of Agriculture, Cairo University, Giza, Egypt African National Agricultural Research Institutes (NARIs)	[48]

2.2 Application of Gene-Editing Tools in Livestock Breeding

Over the past ninety years, animal breeding has advanced significantly through quantitative genetics, statistical methods, artificial insemination, and systematic breeding practices [49]. While genomic selection is widely accepted, genetic engineering and livestock gene editing remain contentious [50]. Although selective breeding and genomic selection can change animal genomes, they lack the precision to manipulate specific traits or alleles. Nevertheless, genetic engineering and genome editing offers new possibilities for improving animal production [51]. Unlike crops such as oilseed rape, soy, and maize, which are generally accepted by consumers for genome editing (particularly for traits like herbicide tolerance and insect resistance), public perception of genome editing in large mammals is largely negative [51]. The creation of polled cattle is among the first uses of genome editing that will have an impact on people's health as it removes the necessity for invasive dehorning [52]. Additionally, it is thought that animals' welfare improves from enhanced disease resistance [51, 53]. The NRAMP1 gene's integration into the bovine genome has increased the resistance of cattle to bovine tuberculosis [53].

Genome editing is being utilized in cattle management to create live-attenuated vaccines for various diseases. Researchers at the International Livestock Research Institute (ILRI) in Kenya have used CRISPR–Cas9 technology to develop potential vaccines for African swine fever, a serious viral disease in pigs [54, 55]. Additionally, genome editing facilitates precision breeding to produce heat-tolerant cattle, enabling them to thrive in harsh African environments [56]. This approach can also modify the gut microbiomes of ruminants to reduce methane emissions, thus mitigating the environmental impact of livestock farming. Table 2 details the application of genome editing tools in African livestock.

Table 2: Summary of application of GE tools in livestock breeding

S/N	Organism	Edited Gene(s)	Method	Outcome	Country of Study	Year of Study	References
1	Swine	A238L(5EL) gene	CRISPR/Cas 9	Development of pig with resistance against African Swine Fever Virus (ASFV) infection	Kenya	2022	[54, 55]
2	Swine	EP402R	CRISPR/Cas9	Development of pig with resistance against African Swine Fiver Virus (ASFV) infection	Kenya	2022	[54, 55]
3	Goat	APOL 1	CRISPR Cas9 system	African indigenous goats bearing the APOL 1 Transgene were generated	Kenya	2021	[56]
4	Cattle	Theileria parva virulence genes	CRISPR CRISPR/Cas9	Development of a powerful and efficient immune response, when animals were vaccinated against East Coast fever	Kenya	2021	[54, 57]

Table 3: A summary of Africa's ongoing and successful GE applications to improve crop production and livestock farming.

Project Title	**Problem**	**Objectives**	**Target gene(s) and phenotype(s)**	**Country of Study**	**Institution**	**References**
Evaluation of Striga resistance in Low Germination Stimulant 1 (LGS1) mutant sorghum	Economic loss of sorghum caused by the parasitic weed Striga	To knock out LGS1 gene in conferring Striga resistance in sorghum.	LGS1 Mutant alleles at the LGS1 locus	Kenya	Kenyatta University	[57]
Application of reproductive biotechnologies to develop a transgenic goat as a model for genetic control of animal diseases	Losses due to animal trypanosomiasis infection in Livestock	To generate African Indigenous goat bearing the APOL 1 transgene	APOL1 gene on ROSA26 locus by CRISPR Cas9 system.	Kenya	ILRI	[57]
Targeted mutagenesis of the CYP79D1 gene via CRISPR/ Cas9-mediated genome editing results in lower levels of cyanide in cassava	Toxic quantities of cyanogenic glycoside linamarin in cassava	To target the mutagenesis of the MeCYP79D1 gene in exon 3	CYP79D1	Kenya	IBR, JKUAT Nairobi, Kenya,	[58]
Breeding Investigations for Developing Durable Resistance to Maize Lethal Necrosis Disease (MLND) and its Causal Viruses in Kenya	Maize lethal MLND	Introduce resistance against MLND	A quantitative trait locus on maize chromosome 6.	Kenya	1. KALRO 2.NARL Kabete	[57, 59]
Genetic improvement of banana for control of bacterial wilt disease	Xanthomonas wilt disease of banana in East Africa.	To develop genome-edited banana resistant to bacterial wilt disease	Disease susceptibility 'S' genes and phenotype	Kenya	IITA	[57, 43]
CRISPR/Cas9 editing of endogenous banana streak virus in the B genome of Musa spp. overcomes a major challenge in banana breeding	Endogenous banana streak virus (eBSV) in the B genome of plantain (AAB)	To inactivate the eBSV by editing the virus sequences	eBSOLV and BSOLV genes	Kenya	IITA	[57, 42]

Table 3: Continued

Project Title	**Problem**	**Objectives**	**Target gene(s) and phenotype(s)**	**Country of Study**	**Institution**	**References**
CRISPR/Cas9 gene editing of *Theileria parva* for the development of vaccine against East Coast fever	Pigs (African Swine Fever Virus ASFV) and cattle (*Theileria parva*) infections	Generation of live-attenuated vaccines	ASFV and Theileria parva virulence genes	Kenya	VB/(AHH) (ILRI)	[54, 57]
Modulation of energy homeostasis in maize to develop lines tolerant to drought, genotoxic and oxidative stresses	Maize – drought susceptibility	1.Engineering of Poly(ADPribosyl)ation pathway to broaden stress tolerance in plants 2. Knock-down of the maize PARP gene expression using CRISPR/CAS9.	Genes: Poly(ADP-ribose) polymerase (PARP1 and PARP2) Phenotype: Maize tolerant to drought, DNA damage and oxidative stresses.	Kenya	1. VCPSB Ghent University, Belgium 2. PTL KU. Kenya	[57, 60]
Feed the Future Striga Smart Sorghum for Africa (SSSfA)	Striga low resistance in sorghum	To develop and commercialize genome edited Striga resistant sorghum, and research capacity in GE.	Low germination loci 1	Kenya Ethiopia	Kenyatta University	[57]
Improving oil qualities of Ethiopian mustard (*Brassica carinata*) through application of CRISPR/CAS 9-based genome editing	Erucic acid in *B. carinata*	ii. To develop *B. carinata* genotype with low erucic and glucosinolate for food and feed application ii. To develop *B. carinata* genotypes with wax ester for industrial application	FAE1, FAD2, GTR1, GTR2, FAR and WS genes	Ethiopia	IB, Addis Ababa University, Addis Ababa	[57, 61]

Table 3: Continued

Project Title	Problem	Objectives	Target gene(s) and phenotype(s)	Country of Study	Institution	References
Genome Editing for improved resistance to Cassava Bacterial Blight (CBB) Disease	Yield and harvest loss due to CBB disease	To develop cassava resistant or with improved tolerance to CBB	MeSWEET10a gene	Nigeria	NRCRI, Umudike, Nigeria	[57, 62, 63]
Multiplex CRISPR/Cas9-mediated genome editing to address drought tolerance in wheat	Abiotic stress	To generate transgenic and stress tolerant wheat plants	*Sal1 Arabidopsis* gene	Egypt	GD, CUE	[57, 64]
High-throughput screening of genes associated with the response of cassava to geminivirus South African cassava mosaic virus (SACMV).	High time response of cassava to cassava mosaic disease (CMD)	To silence the gene associated with the response to SACMV infection and measure the expression of mutant SACMV-infected cassava protoplasts	Ubiquitin proteasome system genes (e.g. E3 ligases), transcription factor genes (e.g. WRKYs), and resistance genes (e.g. NLRs).	South Africa	SMCB, University of the Witwatersrand Johannesburg	[57, 65]
Genome editing of potato	Viral infection in potatoes.	Production of virus-resistant potatoes.	Eukaryotic initiation factor 4E (Eif4E)	South Africa	Stellenbosch University	[57, 66]
Targeted gene editing for the development of high-yielding, stress-resistant and nutritious crops	**Cassava:** 1) Limited knowledge of the molecular basis of flowering 2) Lack of double haploid lines and efficient methods for double haploid induction in cassava **Rice: R**esistance of rice to yellow mottle virus **Maize:** Resistance of maize to lethal necrosis	1. To produce fertile flowers and seeds in cassava 2. To produce stress-resistant, cassava 3. To develop rice resist varieties 4. To develop maize-resistant varieties to lethal necrosis	**Genes:** Phytoene desaturase, Terminal flower 1, Centromere localized genes, Host susceptibility genes **Phenotypes:** Photo bleaching, early flowering**,** short homozygous plants, Virus resistant edited plants	Uganda	1. NARO 2.NaCRRI-Namulonge Campus	[67]

Key: ILRI: International Livestock Research Institute, IBR, JKUAT: Institute for Biotechnology Research, Jomo Kenyatta University of Agriculture and Technology, Nairobi, Kenya, KALRO: Kenya Agriculture and Livestock Research Organization, NARL: National Agricultural Research, IITA: International Institute of Tropical Agriculture, VCPSB: VIBUGENT Center for Plant Systems Biology, Ghent University, Belgium, PTL KU: Plant Transformation Laboratory, Kenyatta University, Kenya, VB/AHH: Vaccine Biosciences/Animal and Human Health (AHH), IB: Institute of Biotechnology, Addis Ababa University, Addis Ababa, NRCRI: National Root Crops Research Institute Umudike, Nigeria, SMCB: School of Molecular and Cell Biology, University of the Witwatersrand Johannesburg, GD-CUE: Department of Genetics, Cairo University Egypt, NARO: National Agricultural Research Organization, NaCRRI: National Crops Resources Research Institute -Namulonge Campus.

3.0 Use of Gene-Editing tools in Health Improvement

The use of GE in the control of human diseases in Africa is limited, however, few studies in the areas of combating artemisinin resistance and clearing chronic hepatitis B virus infection have been reported. The *Pfkelch13* gene in *Plasmodium falciparum* encodes a propeller protein essential for haemoglobin endocytosis, and mutations in its domain are linked to artemisinin resistance [68, 69]. Researchers from East Africa used CRISPR-Cas9 to introduce two specific point mutations (R571H and P574L), previously identified in patient samples from Rwanda [70]. They discovered that the R571H mutation causes artemisinin resistance in vitro, similar to the C580Y mutation, which is prevalent in Southeast Asia and contributes to resistance there [71]. This gene-editing study underscores the potential threat of artemisinin-resistant malaria in Africa [72]. Additionally, gene editing is being explored for treating Hepatitis B Virus (HBV) infections by South African researchers. Current treatments fail to eliminate covalently closed circular DNA (cccDNA), which acts as a reservoir for viral replication. Gene editing aims to address this gap in treatment [72].

Scott *et al* [72] also used CRISPR/Cas9-based technology to insert genes encoding *Staphylococcus aureus* CRISPR-associated protein 9 (SaCas9) and its regulatory elements into recombinant single-stranded adeno-associated viral vectors. This method resulted in the inactivation of HBV replication and blocked cccDNA mutation *in vitro* thus demonstrating the potential for gene editing to aid the fight against chronic hepatitis B infection which affects up to 65 million Africans and increases their risk of liver cirrhosis and hepatocellular carcinoma [73].

4.0 Progress in GE in Africa

Africa's progress in GE marks a significant step forward in applying modern scientific discoveries to address the continent's unique challenges. With the potential to greatly enhance environmental conservation, boost agricultural output, and improve healthcare, this innovation signals the dawn of a new era of possibilities. By leveraging CRISPR-Cas9 technology, Africa is moving towards a brighter future, one defined by strong healthcare systems, lasting food security, and the protection of its diverse ecosystems [74, 75].

Efforts are underway to counter cassava mosaic disease, a threat to food security in Sub-Saharan Africa, by developing resistant cassava cultivars [76]. GE holds promise for treating genetically linked diseases such as sickle cell disease and HIV/AIDS in Africa, with CRISPR technology being explored to correct the genetic flaws causing these conditions [77, 78]. GE is also being researched for biodiversity conservation, using gene drive technology to control invasive species and enhance the survival of endangered species, though these interventions are still experimental [79, 80].

To support GE in Africa, the Innovative Genomics Institute partners with the African Orphan Crops Consortium, the Seed Biotechnology Center, and the International Institute of Tropical Agriculture to train African plant scientists in the use of CRISPR by providing them with tools that will be used in growing varieties of crops to meet the demanding needs of the local communities in Africa and beyond. This training fosters to improvement of crops with the traits to adapt to changes in climate, enhance nutritional value, and make them resistant to plant and disease threats [44, 81]. Additionally, the African Union Development Agency-New Partnerships for Africa's Development (AUDA-NEPAD) and the Pan African University of Science, Technology, and Innovation (PAUSTI) are leading proponents of using GE to reduce hunger and malnutrition [44, 82, 83].

The advancement of GE in Africa is met with debates over ethical, societal, and legal concerns. African countries are working to establish regulatory frameworks that balance innovation with ethical issues like informed consent and potential unforeseen outcomes [84]. A key factor for success is capacity building, which includes developing advanced research facilities, fostering international collaborations, and training African scientists in cutting-edge GE techniques. These efforts aim to empower Africa to set its scientific agenda and address its unique challenges [84].

5.0 Challenges of GE in Africa

Research suggests that GE enhances scientists' ability to manage the existence of various plants and animals, potentially impacting human evolution. Many scientists advocate for a ban or temporary pause on genetic alterations to carefully assess their benefits and drawbacks. Conversely, some argue that despite the ethical concerns and uncertainties, we should embrace scientific progress and continue advancing in this field.

Koloi-Keaikitse *et al*. [85] conducted a comprehensive study examining the cultural values, norms, and beliefs influencing community engagement in genome editing research in Botswana. The research revealed a mix of individual and community perspectives on GE. Participants expressed concerns about fear and anxiety related to the use of GE tools, highlighting potential negative impacts. Trust issues concerning the application of GE were prominent, along with worries about stigma, uncertainty, and sensitivity to GE. Additionally, some individuals indicated that contemporary religious beliefs could impede acceptance of GE, as many modern religions view humans as creations of God [85].

Researchers have found that Africa's experience with genetic modification (GM) has largely been negative, highlighting significant challenges [86, 87]. Key issues include confusion between genetic engineering and GM, leading to biosafety concerns and a lack of regulatory frameworks in many African countries. This situation has necessitated considerable efforts to change public perceptions, as there is a stigma associated with transgenic organisms. Regulatory bodies often struggle to promote GE technologies effectively due to inadequate infrastructure and resources for scientists, including limited access to genetic materials, electricity, internet, lab facilities, equipment, and funding [86]. In response to these challenges, the World Health Organization (WHO) has established the Advisory Committee on Developing Global Standards for Governance and Oversight of Human GE. This committee has produced a Draft Governance Framework on Human GE and includes members from various regions, emphasizing a collaborative approach to governance in this field [88, 89].

Shozi *et al*. [90] identified several critical areas in South Africa that the draft framework for global governance of GE needs to address. First, it must effectively tackle concerns related to demonstrating safety and efficacy, considering that different countries have varying thresholds for risk acceptance. This involves recommending suitable preclinical and clinical testing protocols for heritable gene editing, as well as ensuring the feasibility of intergenerational monitoring. Second, a more nuanced approach is required regarding the intersection of state sovereignty and global standard-setting. When properly regulated from a governmental perspective, medical tourism can help skilled local medical professionals advance their careers and provide genetic engineers and biomedical specialists with invaluable chances to improve their expertise. Third, it fails to recognize that diverse legal systems may have legitimate variations in their interpretations of human dignity. Parents should be granted the freedom to decide whether, when, and how to utilize GE technology unless compelling, evidence-based arguments exist to limit their options. Finally, it is essential to clarify what constitutes an injury to an individual's future interests [90].

In South Africa, Thaldar *et al*. [91] outlined guiding principles for GE aimed at informing moral and legislative reforms related to human germline editing. These principles emphasize the necessity of proper regulation, parental authority regarding GE applications on children, the acceptance of both therapeutic and non-therapeutic GE, the importance of public disclosure and accessibility of safe GE clinical applications, and the need to address social inequality for improved access. Other countries such as Nigeria, Kenya, Malawi and Ghana have published National Biosafety guidelines on GE [44]. Despite the establishment of regulatory systems to oversee GE and address public concerns, a major challenge in Africa is the lack of adequate monitoring and ethical safeguards, which can lead to the misuse of genetic technologies [91].

6.0 Prospects of GE in Africa

Divergent views have emerged over whether the advantages of GE technologies outweigh their disadvantages since their introduction [92]. Many academics and members of the public have similar concerns, such as how genome-edited items that could potentially cause mutations would be found in the future. What potential negative impact on international trade might items with altered genomes have? In the future, how will items that have had their genomes altered or genetically modified organisms be regulated? Is it possible that we will eventually have an international regulation that is harmonized? Prominent academics were prompted to gather and discuss thoughts and prospects about GE technology in Africa by these and other questions.

Aiming to raise awareness of the advancement of technologies and emerging genetic technologies, such as GE, which enable faster, easier, less expensive, and more precise changes to DNA, the Africa Biennial Biosciences Communication Symposium convened on June 13, 2019, and included conversations on the technology, with great opinions and quotations from scientists, regulators, legislators, and scientific communicators [93].

It became clear from their conversation that GE has a lot of potential and would revolutionize the healthcare and agriculture industries globally, not just in Africa. African academics assert that the globe is experiencing a technological revolution, progressing from the green revolution to the gene revolution [93, 94]. Considering this, many countries are actively preparing to approve gene technology of which the nations of Africa have not lagged. The African Union High-Level Panel on Emerging Technologies has already acknowledged that technological improvements are critical to quickening Africa's path of growth and transformation, which promises to greatly benefit the domains of agriculture, health, and animal welfare [93].

Professor Benjamin Ubi of the Department of Biotechnology at Ebonyi State University in Nigeria, an expert in plant breeding and biotechnology, declared during his speech about the potential of GE in Africa that "GE will improve the lives of African farmers by transforming the agricultural sector, increasing productivity, and generating income when adopted." He also added that the African nations should not label the technology's regulation as genetically modified and further encouraged that Africa must build its capability in this area, enact legislation that promotes its application and use, supply the required infrastructure and a favorable research environment, and reward the scientists developing this technology.

The CEO of Kenya's National Biosafety Authority, Prof. Dorington Ogoyi, claims that "GE is one of the newest tools that may be used to address some of the abiotic and biotic constraints in Africa's agricultural productivity." The method offers great promise for crop development as a more precise and quick method. Africa needs to make it very clear which goods, those that have undergone genetic engineering should be subject to regulation and which ones must follow the laws of genetically modified crops.

Dr. Rufus Ebegba, the chair of the Africa Union Biosafety Regulators Forum and director general of Nigeria's National Biosafety Management Agency, stated that "GE holds great prospects for Africa and will create a new vista in biotechnology if adequately and safely applied". With political backing, the African Union should create a roadmap for its expansion and regulation.

Subsequently, there is a need to unify these regulations on a regional level and collaborate when it comes to trade or technical discussions related to the matter. African authorities might learn the most from nations that have previously imposed regulations on this technology. Bibiana Iraqi-Kipkorir, the program manager for Kenya AfriCenter's International Services for the Acquisition of Agro-biotechnological Applications, emphasizes that genetic engineering offers scientists a cost-effective and efficient means to address various agricultural challenges. She advocates for scientists to actively educate the public about GE, highlighting the importance of countering misinformation, especially in the digital age, where non-experts can spread misleading information. Among other scientists, Dr. Charles Mugoya, the Chairman of Uganda's National Biosafety Committee, stated that "public participation and early and continuous conversation are necessary for GE research to increase public trust and acceptance of the technology. Gene editing discussions need to be balanced between optimism and pessimism. The public's trust in Africa's scientists' capacity to make morally sound decisions on GE research must be upheld. The adoption of GE instruments was reinforced by these claims and others, especially in Africa where the technology still seems like science fiction.

Carroll [95] asserted that the field of genetic engineering had progressed exponentially, beginning with oligo-mediated genetic engineering in the 1980s, even in agriculture unquestionably the most important aspect of human existence, while confronting pressures that had never been seen before, such as environmental degradation, hunger, and malnourishment. New GE technologies enable the simultaneous manipulation of several genetic loci in elite varieties [94, 96]. This speeds up crop improvement and improves global food security and the health system. Effective GE, however, requires knowledge about gene functions and genome sequences, which GE may help to some extent supply. The CRISPR tool gained importance over other GE technologies like TALENs and ZFNs because of its affordability and ease of use, which makes it more accessible to research groups [97]. According to Jemaà, [87], GE (CRISPR) is still primarily a molecular biology tool that can be used in any living system and, due to its durability, has become vital for the identification and management of several illnesses. This technology is the way to go because of its features of speed, efficiency, ease of use, adaptability, and precision. This capability will surely lower experimentation costs and make it possible for African labs and researchers to conduct top-notch genetic engineering research [92].

Effective partnerships will be drawn to the quality, and these partnerships will enhance research and education to benefit African nations, especially in low-cost labs. Many agricultural attributes, such as production level, nutritional value, stress tolerance, and resistance to pests and herbicides, have been enhanced through the CRISPR/Cas9 system application [96, 98]. Janik *et al*. [97] argue that while GE technologies have a great deal of therapeutic potential, numerous benefits, the potential to treat serious diseases, and the capacity to "alter the code of life," there are significant ethical and biosafety concerns that should not be ignored [97].

Conclusion

It's a great discovery that African countries have adopted the use of genome editing tools. Our study revealed more applications of GE tools in plant breeding than livestock and human disease treatments. Despite these applications, some ethical challenges still exist. Also, the lack of genome editing facilities and sponsorships in various parts of Africa have impeded the use of these tools, resulting in its application in only a few African countries. This research calls for funders to facilitate African researchers' efforts to improve livestock production, plant breeding, and combating human diseases.

Ethical Approval

Not applicable

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