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

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Africa is grappling with various challenges, particularly in agricultural production and disease prevention affecting humans, animals, and crops. Gene editing, or genome editing (GE), involves modifying, adding, or removing nearly any DNA sequence in various cells and organisms. Due to new techniques, GE is now quicker, less expensive, and more effective. The CRISPR/Cas9 system is based on RNA and has been more effectively tweaked than protein-based methods, enabling multi-site manipulation. The Type II CRISPR system protects DNA from plasmids and viruses that invade it through RNA-guided DNA cleavage by Cas proteins. Several diseases are currently being treated with CRISPR-based GE technology. The raising of livestock is vital to modern society, and it is directly impacted by disease resistance. 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 highlighted limited adoption of 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. BACKGROUND OF THE STUDY

Infectious diseases and food insecurity have hampered economic progress in most countries, especially in low-income African countries (Rohr et al., 2019). The world faces three significant 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 (Searchinger et al., 2019; Tripathi et al., 2022). Mennechet and Dzomo's 2020 report stresses that Africa has the most significant healthcare resource gaps and higher mortality rates due to infectious diseases. African nations should actively implement advanced technologies, such as genome editing, to address these issues to combat health challenges (Mennechet and Dzomo, 2020).

Genome editing (GE) alters an organism's DNA at particular genomic sites to alter biological activities (Saurabh, 2021). This alteration can be accomplished by knocking down undesirable genes or phenotypes, permanently inserting foreign DNA, or activating, overexpressing, or silencing genes (Ledford and Callaway 2020; Karavolias et al., 2021). 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. (2014), GE has enormous potential for developing proactive, effective, and individualized strategies for treating and preventing infectious diseases (Geller et al. 2014). Many scientists have used GE techniques to improve and create novel traits, such as increased therapeutic possibilities, yield potential, stress tolerance, disease resistance, drought resistance, gene therapy, and vaccines (Morishige et al. 2019, Ajami et al. 2020). ‘

GE technologies include transcription activator-like effector nucleases (TALENs), mega-nucleases, zinc-finger nucleases (ZFN), and clustered regularly interspaced short palindromic repeats (CRISPR)/Cas9 (Clark et al. 2023).

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 (Tripathi et al. ,2022). ZFNs are designed explicitly for Cys2-His2 zinc-finger protein and the FokI restriction endonuclease cleavage domain. At the same time, TALENs are derived from bacterial TALEs and comprise an amino-terminal TALE DNA-binding domain connected to a carboxy-terminal FokI cleavage domain (Shukla et al., 2009; Li et al., 2012). The *Streptococcus pyogenes* adaptive immune system is the source of CRISPR/Cas9 (Tripathi et al., 2022). 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 (Javaid et al., 2022). Once the scientific community realized how easy it was to use CRISPR-Cas tools for gene-editing applications, this method quickly became the standard (Javaid et al., 2022). 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 (Josa et al., 2017, Anzalone et al., 2020). 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 (Anzalone et al., 2020).

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 (Lino et al., 2018). 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 developing novel treatments and identifying the function(s) of specific genes (Andoh, 2017). Globally, the GE tools have enabled humankind to experience unthinkable levels of development, and African nations should not 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 what the future holds.

2. 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 (Ricroch et al., 2017; Ricroch, 2019). 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, resulting in significant financial losses (Ndudzo et al., 2024). An entire crop may be lost, depending on how bad the infestation is. For this reason, much work is being done to create crops naturally resistant to biotic stress (Ricroch, 2019). Developing disease-resistant bananas is now feasible with the help of CRISPR/Cas9 and other targeted GE technologies. Because CRISPR/Cas9 GE techniques and comprehensive banana genome sequences are available, constructing disease-resistant bananas is achieved by carefully knocking off the endogenous genes (Ntui et al., 2020). Several susceptibility genes linked to bacterial resistance have been found and targeted for editing in various plants (Tripathi et al., 2023). Research to create genome-edited bananas resistant to bacterial wilt disease is now being conducted at Kenya's International Institute of Tropical Africa (IITA) (Abkallo et al., 2024).

Furthermore, studies have attempted to develop resistance to cassava's two primary and severe viral diseases, cassava Mosaic Disease (CMD) and cassava Brown Streak Disease (CBSD), using CRISPR/Cas9 technology (Gomez et al., 2019; Mehta et al. 2019). A single gRNA was used to silence the viral AC2 and AC3 genes, which play significant roles in gene activation, virus pathogenicity, repression, and replication enhancement (Gomez et al., 2019; Mehta et al. 2019). Mehta et al. (2019) created cassava lines resistant to CMD by engineering transgenic plants to express the Cas9 gene using a guide RNA to target the virus's genome. When tested, the researchers did not observe the resistance of the plants to CMD under greenhouse conditions. This research then led to the whole genome sequencing of the virus and infected wild-type plants, and various mutations occurred within the targeted region of the gRNA, resulting in premature stop codons in the AC2 and AC3 Open Reading Frames (Mehta et al., 2019).

Furthermore, gene editing has successfully created sorghum plants resistant to the damaging parasite known as witchweed (Mbuvi et al., 2017). 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 (Tripathi et al., 2022). TALENs have also been used to develop resistance against worms and fungi in wheat and almonds. 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 (Tripathi et al., 2022).

Scientists are developing a strain of maize resistant to Maize Lethal Necrosis (MLN) using CRISPR-mediated GE without affecting desirable traits and performance (Omondi, 2022). With the GE methods, the MLN Gene Editing Project aims to modify four superior maize varieties resistant to infections (Prasanna et al., 2020). The MLN had reduced maize yields in Kenya, causing enormous losses in productivity and the abandonment of maize planting by many smallholder farmers (Miao et al., 2013). It is possible to develop new MLN-resistant maize cultivars and increase the resilience of already-existing cultivars by using CRISPR editing in maize plants (Liu et al., 2021). If CRISPR-edited maize seedlings are successfully field-planted, food security in African countries will significantly improve in agriculture. GE has focused on modifying, replacing, or regulating genes to develop disease-resistant crops (Liu et al.,2021).

2.1.2 Abiotic stress resistance

Climate change, which causes drought, floods, salinity, and extremely high temperatures, has been an environmental issue scientists have been most concerned about recently (Cardi et al. 2017). Farmers profit from plants' ability to withstand abiotic stressors like cold, salt, drought, and nitrogen shortage (Cardi et al., 2017). Kenyatta University's Plant Transformation Laboratory scientists use CRISPR-Cas9-mediated gene editing to enhance maize lines' resistance to oxidative stress, genotoxicity, and drought. This system has effectively modified various species of plants to improve their tolerance to abiotic stressors (Razzaq et al., 2021). The researchers are explicitly transforming maize varieties, which are susceptible to these stressors, as a result of changes in the gene to develop more resilient lines (Zafar et al., 2020; Razzaq et al., 2021).

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, which is known for improving plants' tolerance to abiotic stress (Sami et al., 2021). Additionally, they are working on creating dwarf and semi-dwarf banana varieties, which are more resilient to storm damage and more straightforward to harvest. The modification of the gibberellin 20-oxidase 2 (GA20ox2) gene in *Musa acuminata* disrupted the gibberellin (GA) pathway (Tripathi et al., 2022). Svitashev et al. (2015) successfully edited genes such as LG1, MS26, MS45, ALS1, and ALS2 in maize, but they had difficulties converting elite lines, mainly commercial hybrids from Africa (Svitashev et al., 2015). The collaborative efforts of African researchers have resulted in the successful transformation of tropical maize lines, making it possible to alter genes in commercial lines directly (Lowe et al., 2018).

Abiotic stressors like reduced soil fertility, unpredictable weather patterns (including floods and droughts), and high temperatures negatively impact yam production. To mitigate these challenges due to abiotic stress, it is essential to develop yam varieties that can adapt to various agro-ecological zones, particularly in low-nutrient soils (Frossard et al., 2017). Ou et al., (2018) highlighted that cassava plants enhance the expression of KUP genes under increased salinity, lower temperatures, and reduced water availability, improving their nutritional quality. The research on gene function in different crops has revealed that several genes respond differently to abiotic stress (Ou et al., 2018).

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 farmers' agronomic and financial challenges, including pest attacks and environmental stresses (Lamichhane et al., 2015). For a long time, the introduction of traditional breeding patterns has boosted agricultural productivity; however, the rising need for food necessitates more efficient crop development techniques (Romero and Gatica-Arias, 2019).

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)	(Tripathi et al., 2019)
Bananas	Bacterial resistance	International Institute of Tropical Agriculture (IITA), Nairobi, Kenya	Consultative Group of International Agricultural Research (CGIAR)	(Tripathi et al. 2021)
Maize	Maize lethal necrosis resistance	Corteva Agriscience	Kenya Agricultural and Livestock Research Institute (KALRO) and the International Centre for Maize and Wheat Improvement (CIMMYT)	(Runo et al., 2024)
Rice	Bacterial leaf blight-resistant rice	Consultative Group of International Agricultural Research (CGIAR)	1. Tanzania Agricultural Research Institute (TARI)-Uyole Centre, United Republic of Tanzania; 2. International Rice Research Institute, Eastern and Southern Africa Region, Kenya; 3. International Rice Research Institute (IRRI), Africa Regional Office, Kenya	(Schepler-Luu et al., 2023)
Rice	Bacterial wilt-resistant rice	AUDA-NEPAD	4. Agence National de Biosecurité (ANB), in Burkina Faso	(Sprink et al., 2022)
Tef	Lodging resistant	Corteva Agriscience	5. Danforth Centre and the Ethiopian Institute for Agricultural Research (EIAR)	(Beyene et al., 2022)
Wheat	Drought tolerance	USDA-ARS, Crop Improvement and Genetics Unit, Albany, USA	Department of Genetics, Faculty of Agriculture, Cairo University, Giza, Egypt 6. African National Agricultural Research Institutes (NARIs)	(Mohr et al. ,2022)

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	(Abkallo et al. 2021, Abkallo et al. 2022)
2	Swine	EP402R	CRISPR/Cas9	Development of pig with resistance against African Swine Fiver Virus (ASFV) infection	Kenya	2022	(Abkallo et al. 2021, Abkallo et al. 2022)
3	Goat	APOL 1	CRISPR Cas9 system	African indigenous goats bearing the APOL 1 Transgene were generated	Kenya	2021	(Nabulindo et al. 2022)
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	(Abkallo et al. 2021, Karembu 2021)

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	(Karembu 2021)
Application of reproductive biotechnologies to develop a transgenic goat as a model for genetic control of animal diseases	Losses due to animal trypanosomiasis infection inLivestock	To generate African Indigenous goat bearing the APOL 1 transgene	APOL1 gene on ROSA26 locus by CRISPR Cas9 system.	Kenya	ILRI	(Karembu 2021)
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	(Juma et al. 2022)
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	(Karembu 2021, Karanja 2021)
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	(Karembu 2021, Tripathi et al. 2021)
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	(Tripathi et al. 2019, Karembu 2021)
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)	Abkallo et al. 2021, Karembu 2021
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	Genes: Poly(ADP-ribose) polymerase (PARP1 and PARP2)	Kenya	1. VCPSB Ghent University, Belgium 2. PTL KU. Kenya	(Njuguna et al. 2017, Karembu 2021)

Project Title	Problem	Objectives	Target gene(s) and phenotype(s)	Country of Study	Institution	References
		2. Knock-down of the maize PARP gene expression using CRISPR/CAS9.	Phenotype: Maize tolerant to drought, DNA damage and oxidative stresses.			
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	Karembu 2021
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	(Karembu 2021, Abdullah 2022
Improving oil qualities of Ethiopian mustard (*Brassica carinata*) through application of CRISPR/CAS 9-based genome editing	Erucic acid in *B. carinata*	i. 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	(Karembu 2021, Tesfaye et al. 2024)
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	(Veley et al. 2020, Veley et al. 2021, Karembu 2021)
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	South Africa	SMCB, University of the Witwatersrand Johannesburg	(Karembu, 2021, Ramulifho 2021)

Project Title	Problem	Objectives	Target gene(s) and phenotype(s)	Country of Study	Institution	References
			resistance genes (e.g. NLRs).			
Genome editing of potato	Viral infection in potatoes.	Production of virus-resistant potatoes.	Eukaryotic initiation factor 4E (Eif4E)	South Africa	Stellenbosch University	(Karembu 2021, Schwegler 2023)
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**, s**hort homozygous plants, Virus resistant edited plants	Uganda	1. NARO 2.NaCRRI-Namulonge Campus	(Odipio et al. 2017)

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.

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

2.2 Application of Genome 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 (Theunissen 2012). While genomic selection is widely accepted, genetic engineering and livestock gene editing remain contentious (Telugu et al. 2017). 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 (Bruce 2017). Unlike crops such as oilseed rape, soy, and maize, which consumers generally accept for genome editing (particularly for traits like herbicide tolerance and insect resistance), public perception of genome editing in large mammals is mainly negative (Bruce 2017). The creation of polled cattle is among the first uses of genome editing that will impact people's health as it removes the necessity for invasive dehorning (Carlson et al. 2016). Additionally, animals' welfare is thought to improve from enhanced disease resistance (Bruce 2017, Petersen 2017). The NRAMP1 gene's integration into the bovine genome has increased the resistance of cattle to bovine tuberculosis (Petersen 2017).

Genome editing is used 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 severe viral disease in pigs (Abkallo, 2021; Abkallo, 2022). Additionally, genome editing facilitates precision breeding to produce heat-tolerant cattle, enabling them to thrive in harsh African environments (Nabulindo et al., 2022). 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.

3. USE OF GENE-EDITING TOOLS IN HEALTH IMPROVEMENT

The use of GE in controlling human diseases in Africa is limited. However, few studies have been reported on combating artemisinin resistance and clearing chronic hepatitis B virus infection. The *Pfkelch13* gene in *Plasmodium falciparum* encodes a propeller protein essential for haemoglobin endocytosis, and mutations in its domain are linked to artemisinin resistance (Birnbaum et al. 2020; York, 2020). Researchers from East Africa used CRISPR-Cas9 to introduce two specific point mutations (R571H and P574L) previously identified in patient samples from Rwanda (Uwimana et al. 2020). 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 (Imwong et al., 2017). This gene-editing study underscores the potential threat of artemisinin-resistant malaria in Africa (Scott et al. 2017). Additionally, South African researchers are exploring gene editing to treat Hepatitis B Virus (HBV) infections (Scott et al. 2017). 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 (Scott et al. 2017).

Scott et al*.* (2017) 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. It 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 (WHO, 2024).

4. 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 significantly 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 defined by strong healthcare systems, lasting food security, and protecting its diverse ecosystems (Chattopadhyay 2018; Giller et al. 2021).

Efforts are underway to counter cassava mosaic disease, a threat to food security in Sub-Saharan Africa, by developing resistant cassava cultivars (Shilomboleni and Ismail, 2023). 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 (Kwarteng et al. 2017; George-Opuda et al. 2024). 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 (Blix et al. 2021; Reynolds 2020).

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. This training fosters the improvement of crops with the traits to adapt to changes in climate, enhance nutritional value, and make them resistant to plant and disease threats (Runo et al. 2024; Innovative Genomics Institute 2024). 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 (Jamnadass et al. 2020; Runo et al. 2024, AUDA-NEPAD 2024).

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 (Ali et al. 2021). 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 (Ali et al., 2021).

5. 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 assess their benefits and drawbacks carefully. Conversely, despite the ethical concerns and uncertainties, we should embrace scientific progress and continue advancing in this field.

Koloi-Keaikitse et al., (2024) 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 (Koloi-Keaikitse et al., 2024).

Researchers have found that Africa's experience with genetic modification (GM) has largely been negative, highlighting significant challenges (Rock et al. 2023; Jemaà 2023). Key issues include genetic engineering and GM confusion, 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 need help 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 (Rock et al. 2023). 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 (WHO 2019; WHO 2021).

Shozi et al. (2021) identified several critical areas in South Africa that the draft framework for global governance of GE needs to address:

1. 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 and ensuring the feasibility of intergenerational monitoring.
2. A more nuanced approach is required regarding state sovereignty and global standard-setting. When regulated adequately 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.
3. 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, clarifying what constitutes an injury to an individual's future interests (Shozi et al., 2021).

In South Africa, Thaldar et al. (2020) 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 (Runo et al., 2024).

Despite establishing regulatory systems to oversee GE and address public concerns, a significant challenge in Africa is the need for adequate monitoring and ethical safeguards, which can lead to the misuse of genetic technologies (Thaldar et al., 2020).

6. PROSPECTS OF GE IN AFRICA

Divergent views have emerged over whether the advantages of GE technologies outweigh their disadvantages since their introduction (Zhang et al., 2022). Many academics and public members 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? How will items with genomes altered or genetically modified organisms be regulated in the future? Will we 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. It included conversations on the technology, with fantastic opinions and quotations from scientists, regulators, legislators, and scientific communicators (Karembu, 2019).

It became clear from their conversation that GE has much 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 (Karembu 2019; Davies, 2003). Considering this, many countries are actively preparing to approve gene technology, of which the nations of Africa have yet to lag. 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 benefit the domains of agriculture, health, and animal welfare significantly (Karembu, 2019).

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 favourable 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 regarding trade or technical discussions related to the matter. African authorities might learn the most from nations that have previously imposed regulations on GE. 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 educate the public about GE actively, 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. These claims and others reinforced the adoption of GE instruments, especially in Africa, where the technology still seems like science fiction.

Carroll, (2017) 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 (Carroll, 2017). New GE technologies enable the simultaneous manipulation of several genetic loci in elite varieties (Davies 2003; Hsieh et al. 2019). This speeds up crop improvement and improves global food security and health. Effective GE 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 (Janik et al., 2020). According to Jemaà (2023), 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 identifying and managing several illnesses. This technology is the way to go because of its speed, efficiency, ease of use, adaptability, and precision. This capability will lower experimentation costs and enable African labs and researchers to conduct top-notch genetic engineering research (Zhang et al., 2022).

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 (Hsieh et al. 2019; Jackson et al., 2019). Janik et al. (2020) 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 (Janik et al. 2020).

7. CONCLUSION

It is a great discovery that African countries have adopted 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 need for genome editing facilities and sponsorships in various parts of Africa has impeded the use of these tools, resulting in their 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.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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