Enhancing Food Safety in Africa: The Role of Molecular Biology Approaches

.

ABSTRACT

Reports by the world health organization reveal that food contaminants and pathogens contribute immensely to high mortality rates amongst people year in and out. The timely control, detection, and identification of these substances and organisms in food is particularly challenging in several African nations. Highly efficient molecular techniques such as polymerase chain reaction (PCR) and gene chip technology are widely adopted. Molecular techniques have paved the way for identification, genotyping, monitoring of food contamination sources, and detection methods via genetic markers. This review seeks to provide an overview of the rapidly improving molecular techniques and their use in the development or enhancing food safety framework, at the same time tracing the progress of Africa in terms of the use of these molecular approaches in curbing or reducing food safety challenges in the region. Several molecular approaches are crucial for the detection of microbes in foodstuffs. However, the lack of sophisticated molecular approaches and precision of data and interpretation arise from the poor or inadequate use of molecular biology techniques in Africa. The molecular techniques adopted in food are more reliable, precise, accurate, and faster alternatives than biochemical, physicochemical, physical, and chemical methods. This review also captures the future perspectives of molecular methods - next-generation sequencing in food diagnostic and microbiology in Africa.

*Keywords: [*PCR, genotyping, next-generation sequencing, food diagnostic*]*

1. INTRODUCTION

1.1 Overview of Food Safety in Africa

Africa generally has being well known for its large scale production of food and agricultural products; this is perhaps owing to the vast land of the region and also the large population of the continent to meet food sufficiency. Despite that, food safety, food quality and nutrition have, overall, been given lesser priority until recent years. According to the World Health Organization, it is estimated that, 91 million people in Africa fall ill each year due to food-borne diseases and 137,000 die of the same cause, representing one-third of the global death toll for foodborne diseases.

Food-borne diseases (FBD) are common public health problems experienced daily, which are part of several outbreaks that worsen the health quality of the world's population and economy [1]. Food-borne diseases can result from consuming food and water that has been contaminated with micro-organisms and toxins [2]. Also, poor processing, preparation, storage, and other inadequate food safety practices are linked to the spread of food-borne diseases [1, 3]. The hazards associated with food-borne diseases occur in the various stages of food production - from "farm to fork'' [4, 2]. Immediately contaminated food gets to

the consumer, it can result in severe clinical conditions and death in some cases [2]. Food hazards can influence public health and result in serious economic damage Food hazards can influence the public health and result in serious economic damage [5]. Food-borne diseases occur more frequently in low-income countries of developing regions where hygiene, sanitation, and safe food handling practices are low [6, 1]. It is also shown that 31 food-borne diseases caused an estimated 600 million diseases and 420,000 deaths, and the higher risk was in developing countries [2, 7]. Millions of people globally become ill from food and waterborne diseases. It is estimated that about three million people die every year, of which 700,000 of these deaths occurring in Africa due to diarrhea alone, associated with contaminated food and water. Occurrence of such disease can easily aggravate to a food safety emergency situation, which can negatively impact national economies and livelihoods through reduced availability of food for domestic consumption, closure of export markets. Albeit, cases of foodborne illness occur daily in all countries around the world, there is no or inadequate reporting of such diseases, particularly in developing countries, including Africa. Consequently, the true prevalence of foodborne disease in Africa and the rest of the world are unknown [8].

There is fragmented and insufficient information on food safety in the African region. This is mainly due to lack of surveillance, documentation and reporting, thereby resulting in inefficient utilization of resources, duplication of activities, and lack of synergy among the countries of the region [9]. Food safety is not regarded a priority among most, if not all African governments, particularly for domestic populations, and is often seen as separate from public health. The harsh reality is that Africa experiences many other challenges, which take priority in many instances. In 2012, 90% of malaria- related deaths occurred in Africa, numbering almost 600 000. Primary health care, provision of education, treatment of human immunodeficiency virus/acquired immune deficiency syndrome (HIV/AIDS), supporting undernourished people, and enhancing food security are all important issues for Africa, requiring considerable spend, placing beleaguered budgets under pressure. According to the Food and Agriculture Organization [10] (FAO, 2010), of the 925 million undernourished people in the world in 2010, Sub-Saharan Africa (SSA) had the highest proportion at 30%, which translates into 239 million people. With regards to HIV/AIDS (Note that HIV is not considered as a foodborne pathogen However, it is relevant to food safety, as it can potentially be transmitted through breast milk. Also, HIV infections create vulnerability to other foodborne infections.), SSA remains the most heavily affected region, with an estimated 23.5 million infected people in 2011, representing 69% of the global HIV burden. In addition, 92% of pregnant women living with HIV/AIDS and 90% of children who acquired HIV in 2011 are found in SSA [11].

Globally, or more importantly in Africa, food safety systems have not kept pace with the complexity of food safety challenges. In Africa, these challenges include, among others, poor food safety management and mandate, and little or no investment and budgetary finances on sanitary and phytosanitary (SPS) – related quality infrastructures [12, 13]. The challenges are further aggravated by the poor food safety culture in the continent. These challenges of unsafe food have undermined the pace and state of food system transformation in the continent. This is because unsafe foods adversely impact public health but also thwart efforts at boosting trade in food and agricultural commodities and reduce agricultural trade, thereby leading to loss of earnings and income [14, 15].

Hunger is a serious challenge in Africa. It is mainly caused by food insecurity, and can only be mitigated by enhanced food safety and food security. Food safety has a tremendous impact in ensuring food security. The main cause of food insecurity is the decline in global food productivity. It is also a problem of poverty which has adverse effect on the socio-economic life of its citizens. Africa is so blessed with land resource that if well utilized towards agricultural productivity will greatly impact food security and sustainability. Agriculture, of which 85 to 90 per cent is rain-fed in sub- Saharan Africa, accounts for 35 percent of the region's gross national product (GNP), 40 percent of exports and 70 percent

of employment. There is need to focus more on agricultural innovations in Africa, so as to boost food output in the region. It is important that provision of safe and production of food be given the attention it deserves by addressing the numerous challenges facing it so as to stimulate economic growth and ensure food security and safety in the African continent [16].
The use of technological advances would help in enhancing the detection of foodborne hazards and improved diagnoses of foodborne illness and thus would play a crucial role in addressing food safety and food insecurity challenges. There are various emerging trends in food safety that will be of paramount importance in effectively and smartly circumventing food safety problems in African countries and becoming competitive in the continental and global food trade.
The use of molecular biology approaches are among the major breakthroughs globally used in addressing food safety.

1.2 Molecular Biology and Food Safety

Several approaches and techniques are been used for the detection of contaminants, pathogens or microorganisms in food stuff. However, in recent times, the concern for precision and rapid approaches in addressing food safety challenges has led to the birth of molecular biology techniques or approaches in tackling food safety challenges. The use of molecular biology techniques that basically use nucleic acids and antibodies in the detection of foodborne pathogens came up in the late 20th and early 21st century. For almost a century, food analysts have relied almost exclusively on conventional microbiological testing methods, consisting of culture media, for growing and isolating bacterial pathogens in foods. Food diagnostics yet remains a challenging task owing to the complexity of the food menstruum and the heterogeneity of various food matrices [17]. Scientific advances have introduced a number of molecular biological diagnostic assays that have had a tremendous impact on methods used for the detection of foodborne pathogens and their toxins.
Over the last 2 decades, there have been tremendous progresses in the development and use of molecular techniques for the detection of microorganisms in foodstuffs as a result of the increasing demand for rapid results. These are normally based on detecting specific DNA or RNA target sequences using amplification processes, in particular the polymerase chain reaction (PCR) [18]. Their adoption, in many instances, has replaced or supplemented traditional culture detection methods with culture methods still recognized as the gold standard for most bacterial foodborne pathogens. But in the case of some foodborne viruses, which are not culturable, nucleic acid-based assays remain the only choice for their detection. Microbial (bacterial or viral)-derived nucleic acids may enter the food chain from similar reservoirs as indicated for the pathogens themselves. Intact living cells will possess intact DNA/RNA, although dead cells may also house intact nucleic acids. Furthermore, the presence of fragmented extracellular nucleic acids emanating from microbial or viral sources cannot be excluded in foods. For example, adventitious viral nucleic acids have been detected in the porcine-derived trypsin enzyme [19].
Recently, breakthroughs have been witnessed in the aspect of the use of molecular biology in enhancing food safety. The adoption of data-intensive tools in food safety, which are emerging so rapidly, is spearheading the early stages of a grand overhaul that is proposed to usher in an era of implementing new approaches to food safety with high precision research. While a number of approaches, such as Geographic Information Systems (GIS) technologies play essential roles in high precision researches in food safety, omics technologies are one of the key drivers of this movement [20-22]. In particular, whole genome sequencing (WGS) not only allows for highly sensitive “precision” subtyping that facilitates considerably improved detection of foodborne disease outbreaks [23-25], but also allows for comprehensive characterization of foodborne pathogens and identification of strains and clonal groups that differ in virulence and antimicrobial resistance [26-28]. The practical use of metagenomics and meta-transcriptomics for detection of food pathogens and even pathogens found in human has started making headway, while WGS is still becoming increasingly used in routine surveillance of foodborne pathogens [29-31].

The use of WGS in bacterial population genomics has tremendously increased the understanding of genome evolution and biology of bacterial pathogens [32, 33]. While genome sequencing was initially expensive, the introduction of next generation sequencing technologies and less expensive small bench top sequencers has decreased the overall sequencing costs [34]. This made the per isolate cost of microbial WGS to a point where it is comparable or even below the price range of traditional subtyping methods (e.g., Pulsed Field Gel Electrophoresis [PFGE]) and made WGS an indispensible tool in modern outbreak investigations. Of the earliest reports on the use of WGS in the investigation of a foodborne disease outbreak was made by Gilmour et al. [35], describing the genome sequences of two distinct Listeria monocytogenes strains involved in a multi-province outbreak in Canada in 2008. The first report of the use of WGS to infer the potential source of a foodborne outbreak was by Lienau et al. [36], involving isolates of the multistate outbreak of Salmonella Montevideo which occurred between July 2009 and May 2010.

Herein, we provide an overview of the rapidly improving molecular biology techniques and their use in the development or enhancing food safety framework, while at the same time tracing the progress of Africa in terms of the use of these approaches in curbing or reducing food safety challenges in the region.

2. CURRENT MOLECULAR BIOLOGY & BIOTECHNOLOGY TECHNIQUES IN FOOD SAFETY

Relevance/Applicability of Molecular Biology Techniques to Food Safety Molecular Biology Techniques Polymerase Chain Reaction (PCR), Expression cloning, array, biosensors, Gel electrophoresis, Macromolecule blotting, and probing are amongst notable techniques which have significantly led to advances in novel food development, traceability, food authentication, and genetic modification [37].

PCR-RFLP and PCR are reliable molecular techniques for detecting adulterations in various meat products [38]. It is imperative to identify animal species adopted in meat production on a commercial scale, especially considering the sanitary and economic aspects. Polymerase chain reaction-restriction fragment length polymorphism (PCR-RFLP) assay was adopted to examine equine and ruminant animal species used in Egyptian sausage and minced meat. Real-time PCR has gained much attention as an effective nucleic acid-based technique due to its relatively high precision, speed, and reproducibility. It is notably adopted for quality control and analysis in the food safety sector [39, 40]. Real-Time PCR approach by Kabacaoğlu and Karakaş [41] detected adulteration in starch-based products. The findings revealed DNA measurement with high-level precision. Research carried out by Sobrino-Gregorio et al. [42], adopted the Real-Time PCR method to examine the inclusion and incorporation of sugar from various plant sources in honey. Villa et al. [43] also developed a Real-Time PCR-based approach for detecting saffron plant products' adulterations. The nucleic acid consisting of the targeted gene region should be sufficiently extracted in analysis using the Real-Time PCR technique to obtain high precision. Quantitative approaches are commonly adopted in analyzing GMO and pathogen microbes in food quality control labs, while qualitative approaches analyze meat type, milk origin, and allergen effectively. Raising the frequency of usage of Real-Time PCR methods will most likely prevent food adulteration.

Several food control agencies and related food industries have adopted the ELISA method to investigate the presence and abundance of allergenic proteins in food products [44]. Western blotting technique is also often adopted in the identification and separation of proteins and food allergen detection [45]. This technique detects a specific protein in a blood or tissue sample by utilizing gel electrophoresis to separate proteins in samples and detect proteins and antigen-antibodies [46].

The detection of food pathogens is crucial in food safety endeavours. The use of lateral flow assay (LFA) as well is used as an advanced technique in food pathogen detection; it gives

high-level sensitivity, short detection time, and operation proffer an apt avenue for on-target detection [47]. This method has become quite popular because of its capacity to quantify and detect pathogens and proteins onsite and at a relatively rapid and cheap rate.

.

3. ADVANCEMENTS IN MOLECULAR BIOLOGY FOR FOOD SAFETY IN AFRICA

3.1 Overview of studies and research initiatives focused on food safety in Africa

Research on food safety in Africa has focused on various aspects, including mycotoxin contamination, the potential of genetically modified organisms (GMOs) in addressing food security challenges [48], and the role of fermented dairy products in enhancing food safety [49]. Aryee et al. [50] highlights the potential of genomics in improving animal and crop production for food security in sub-Saharan Africa, but also identifies challenges such as the lack of resources and capacity. These studies collectively underscore the need for continued advancements in molecular biology to address food safety issues in Africa.

Obidiegwu et al. [51] have investigated the state of abattoir operations and waste management in Sub-Sahara Africa (Nigeria) identifying challenges and prospects for environmental quality and public health in the industry. They identified Public Health Challenges in Somachi Main Abattoir, Owerri" and recommended upgrading the abattoir to meet modern standards and enhancing education and training for hygiene practices. Furthermore, the presence of heavy metals and chemical substances in food has been addressed, with a focus on their potential health risks and implications.

Researches have also underscored the importance of addressing knowledge gaps and poor hygiene practices among food handlers and vendors in Nigeria and Ghana. It also emphasizes the need for improved regulation and enforcement of food safety laws to mitigate food contamination at various stages of the food production chain. Literatures also revealed the predominant etiological agents isolated in Ghanaian and Nigerian foods, such as *Enterobacter spp., Pseudomonas spp., Campylobacter spp., Escherichia coli, Staphylococcus spp., Aspergillus flavus,* and *Aspergillus niger*, shedding light on the microbial safety challenges faced in the region [52]. There is a multifaceted nature of food safety challenges in Sub-Saharan Africa, highlighting the need for comprehensive research, improved hygiene practices, and rigorous enforcement of regulations to ensure food safety and mitigate public health risks. Additionally, there is necessity of addressing knowledge gaps, enhancing education and training, and implementing effective regulatory measures to safeguard the food supply chain [52].

3.2 Successful Projects and Collaborations Utilizing Molecular Biology Techniques in Africa

Advancements in molecular biology for food safety in Africa have been demonstrated through successful projects and collaborations. South Africa and Argentina have been at the forefront of molecular farming, producing experimental therapeutics and vaccines for livestock and human diseases [53]. Genetically modified crops have also been explored in Africa, with a focus on biosafety processes and policies [54]. The potential of genomics in sustainable agricultural research for food security in sub-Saharan Africa has been highlighted, with a call for the use of local resources and capacity-building [50]. However, challenges such as funding, lack of practical application, and disparate attitudes towards biosafety regulation have been identified [55]. These findings underscore the need for continued investment and collaboration in molecular biology for food safety in Africa.

3.3 Decision Making Tools to Aid Rejection or Implementation of GM Crops in SSA

Arthur and Yobo [54], reported a decision-making tool which will help to address the issue of whether to implement GM crop cultivation in some Sub-Saharan African Countries or not. It is a structured and a reasoned approach that has the potential to assist in the identification or the discovery of genetically modified organisms potential to cause adverse harm and to

characterize the seriousness and the likelihood of potential harm [56]. Johnson et al. [57] suggests two decision making tools that can help policy makers reach a consensus. Scientific risk assessment and Risk analysis methods will prove useful in regulatory decision making concerning the implementation of GM crops. In a nut shell Risk assessment forms the foundation for regulatory decisions on whether to authorize the environmental release of GM organisms [56]. Scientific decision-making tools such as environmental impact assessments, Life Cycle Assessments (LCA's) also known as "Cradle to the grave analysis" if implemented in Sub-Saharan African countries can help to evaluate the impacts of GM crops on its surrounding environment throughout its life cycle [58].

3.4 Bio-fortified Maize Production

Although not a silver bullet solution, bio-fortification has proven to be an efficient strategy to combat malnutrition. CIMMYT, IITA, and national partners especially in Africa, Asia, and Latin America have employed conventional breeding and molecular tools, to successfully develop and release several nutritious maize cultivars without compromising grain yield levels or other important agronomic and adaptive traits. Many of these bio-fortified maize cultivars are currently grown by farmers and accepted by consumers in many countries [59]. Advances in phenotyping coupled with molecular breeding facilitated achievement of the breeding targets for various nutrients in maize.

3.5 Genome Editing to Produce Disease Resistant Crops for Sustainable Agriculture in Africa

Genome editing efforts towards developing disease-resistant crops have focused on gene disruption, replacement, or regulation. For instance, disrupting negative regulators of plant disease resistance such as host susceptibility (S) genes could offer durable resistance to diseases. This strategy could durably offer resistance to yam viruses by knocking out eukaryotic translation initiation factors (eIFs). In plants, eIFs are translation initiation factors that mediate the replication of plant RNA viruses, majorly potyviruses [60]. Therefore, targeting these genes in yam could curb potyvirus infestations such as yam mosaic virus, as reported in cassava [61] and cucumber [62]. On the other hand, yam badnaviruses could be managed by targeting viral sequences integrated in host plant genomes, as demonstrated in banana [63].

Susceptibility genes, mainly the mildew locus O (*MLO*), enhanced disease resistance *1* (*EDR1*), and the Non-Expressor of Pathogenesis-Related 3 (*NPR3*), could also represent good genome editing targets for generating resistance to fungal diseases in yam [64]. Since the fungal disease anthracnose is the most widespread foliar disease in yam [65], developing endogenous resistance would alleviate the associated yield losses, ensuring food security for an economically disadvantaged population. Moreover genes that are highly conserved across plant species and have successfully generated plant fungal resistance, such as *WRKY* transcription factors and *ERF922,* could be precisely modified to achieve these endeavours. The precise modification of host susceptibility genes such as *DMR6* and *SWEET* could be affected to confer food yam with resistance to bacterial diseases. Further, the upregulation of host resistance genes is also a feasible approach for generating disease-resistant yam lines [66].

4. CHALLENGES AND OPPORTUNITIES IN IMPLEMENTING MOLECULAR BIOLOGY APPROACHES

Molecular biology approaches are of great importance in enhancing food safety in Africa. However, it is saddening that there are lots of challenges impeding the implementation of molecular biology approaches in Africa. Many African countries face significant challenges in infrastructure and resources, which can impede the implementation of advanced molecular biology techniques. For instance, genetically modified organisms (GMOs) are seen in

relation to food safety and security within the continent, addressing challenges like hunger and malnutrition [48].

However, hurdles such as pathogenic microorganisms, disease-ridden animals entering the food chain, and chemical contaminations are prominent sources of food poisoning that need to be managed [67]. Resources and infrastructures play great roles in the implementation of molecular biology approaches in enhancing food safety in Africa. However, applying molecular biology techniques to solving problems in Africa is a difficult task brought about by a lot of infrastructural problems such as unreliable or no electricity in laboratories, especially considering that these equipment use electricity and even sample storage at specific temperatures requires a stable and reliable power supply [68]. Also, there are very limited numbers of well-equipped laboratories, which implies that samples will need to travel long distances to get to the laboratories in some cases, facing the challenges of the bad and impassable roads [69], which often lead to sample degradation and loss of integrity [70-72]. Most of the laboratories with functional molecular biology research capacity were either established, and/or sustained by foreign or international funding and partnerships, or private sector intervention [73, 74].

4. FUTURE DIRECTIONS AND RECOMMENDATIONS

To further enhance food safety in Africa using molecular biology approaches, it is essential to expand the implementation of advanced molecular techniques such as next-generation sequencing (NGS) and metagenomics. These techniques should become integral parts of routine monitoring and surveillance systems for foodborne pathogens, providing comprehensive and real-time data on microbial communities and their dynamics in various food matrices. Additionally, developing local capacities through extensive training programs and upgrading laboratory infrastructure are vital. Investment in modern equipment and consistent supply of necessary reagents and consumables will ensure high-throughput and accurate molecular analyses.

Collaboration and networking among African countries are crucial for sharing resources, expertise, and data. Establishing regional centers of excellence in molecular food safety can help standardize protocols and coordinate efforts across the continent. Public-private partnerships should also be encouraged to drive innovation and facilitate the practical application of molecular techniques in food safety practices. Integrating molecular data with traditional microbiological methods can enhance the robustness of food safety diagnostics, improving both sensitivity and specificity in pathogen detection.

Policymakers should focus on developing harmonized food safety standards and regulations across African countries, incorporating molecular biology techniques for pathogen detection and monitoring. Establishing clear regulatory frameworks for the use of genetically modified organisms (GMOs) and other biotechnological advancements in food safety is also necessary. Funding focused research programs that address local food safety challenges and develop tailored molecular solutions should be a priority. Innovations in detection methods, such as the development of novel molecular assays and portable diagnostic tools for rapid on-site testing, should be encouraged to reduce reliance on centralized laboratory facilities.

Public awareness campaigns should be launched to educate consumers about the benefits of molecular techniques in ensuring food safety and highlight the importance of safe food handling practices. Engaging various stakeholders, including policymakers, food industry representatives, and community leaders, in discussions about the role of molecular biology in food safety can garner support and collaboration. Implementing molecular techniques for environmental monitoring of food production areas and promoting sustainable agricultural

practices, such as breeding disease-resistant crops and optimizing pesticide use through precision agriculture, are essential for maintaining long-term food safety and security in Africa.

By focusing on these future directions and recommendations, African nations can significantly enhance their food safety frameworks, reduce the burden of foodborne diseases, and improve public health outcomes across the continent. The integration of advanced molecular techniques, capacity building, collaborative networks, and supportive policies will collectively contribute to a more secure and sustainable food supply.

5. CONCLUSION

As scientific discoveries and technologies advance, molecular biology approaches will find more in-depth applications in ensuring safer foods for all. Advances in novel detection approaches for food-borne allergens and pathogens are particularly relevant for the African scientific community as they serve as potential alternatives.

CONSENT

Authors have declared no competing interests exist.

REFERENCES

References

[1] Lubis NDA, Amelia S, Arrasyid NK, Rozi MF. Modelling of risk factors associated with foodborne disease among school-aged children in Medan, Indonesia. Open Access Maced J Med Sci. 2019;7(19):3302.

[2] Isoni Auad L, Cortez Ginani V, Stedefeldt E, Yoshio Nakano E, Costa Santos Nunes A, Puppin Zandonadi R. Food safety knowledge, attitudes, and practices of Brazilian food truck food handlers. Nutrients. 2019;11(8):1784.

[3] Yenealem DG, Yallew WW, Abdulmajid S. Food safety practice and associated factors among meat handlers in Gondar town: a cross-sectional study. J Environ Public Health. 2020;2020.

[4] Boughattas S, Behnke JM, Al-Sadeq D, Ismail A, Abu-Madi M. Cryptosporidium spp., prevalence, molecular characterisation and socio-demographic risk factors among immigrants in Qatar. PLoS Negl Trop Dis. 2019;13(10).

[5] Food and Agriculture Organization (FAO). Food Handlers: Manual Instructor. Washington, D.C., USA: Food and Agriculture Organization; 2017.

[6] Arisukwu OC, Olaosebikan D, Asaleye AJ, Asamu F. Feeding habit and the health of undergraduate students: evidence from Nigeria. J Soc Sci Res. 2019;5(2):498-506.

[7] Obidoa JC, Onyechi KCN, Chukwuone CA, Dimelu IN, Victor-Aigbodion V, Eseadi C, et al. Gender effect on eating habits of Nigerian school children. Medicine (Baltimore). 2021;100(13).

[8] Anelich L. Foodborne Diseases: Prevalence of Foodborne Diseases in Africa. In: Encyclopedia of Food Safety. Elsevier Ltd.; 2014. p. 262–75.

[9] Paudyal N, Anihouvi V, Hounhouigan J, Matsheka MI, Sekwati-Monang B, Amoa-Awua W, et al. Prevalence of foodborne pathogens in food from selected African countries – A meta-analysis. Int J Food Microbiol. 2017;249:35–43.

[10] Food and Agriculture Organization (FAO). The State of Food Insecurity in the World. Available at: http://www.fao.org/docrep/013/i1683e/i1683e.pdf (accessed on 20 December 2012); 2010.

[11] UNAIDS. Sub-Saharan Africa: A Decline in New HIV Infections and AIDS- Related Deaths. Regional Fact Sheet 12. Available at: http://www.unaids.org/en/media/unaids/contentassets/documents/epidemiology/2012/gr2012/2012_FS_regional_ssa_en.pdf; 2012.

[12] Czubala W, Shepherd B, Wilson JS. Help or hindrance? The impact of harmonised standards on African exports. J Afr Econ. 2009;18(5):711-44.

[13]Jaffee S, Henson S. Standards and agro-food exports from developing countries: rebalancing the debate. World Bank Publications; 2004.

[14] Kareem FO, Martínez-Zarzoso I. Are EU standards detrimental to Africa's exports? J Policy Model. 2020;42(5):1022-37.

[15] Kareem FO, Martínez-Zarzoso I, Brümmer B. What drives Africa's inability to comply with EU standards? Insights from Africa's institution and trade facilitation measures. Eur J Dev Res. 2023;35(4):938-73.

[16] Onwujekwe EC, Chinyere Ezemba C. Food Security and Safety: Africans Perspectives A Review. Arch Curr Res Int. 2021 ;(February):14–20.

[17] Feng P. Impact of Molecular Biology on the Detection of Foodborne Pathogens. Appl Biochem Biotechnol - Part B Mol Biotechnol. 1997;7(3):267–78.

[18] Cocolin L, Rajkovic A, Rantsiou K, Uyttendaele M. The challenge of merging food safety diagnostic needs with quantitative PCR platforms. Trends Food Sci Technol. 2011;22.

[19] Victoria JG, Wang C, Jones MS, Jaing C, McLoughlin K, Gardner S, Delwart EL. Viral nucleic acids in live-attenuated vaccines: detection of minority variants and an adventitious virus. J Virol. 2010;84(12):6033-40.

[20] Beni LH, Villeneuve S, LeBlanc DI, Delaquis P. A GIS-based approach in support of an assessment of food safety risks. Trans GIS. 2011;15(s1):95-108.

[21] Wang J, Jia H. Metagenome-wide association studies: fine-mining the microbiome. Nat Rev Microbiol. 2016;14:508-22.

[22] Weller D, Shiwakoti S, Bergholz P, Grohn Y, Wiedmann M, Strawn LK. Validation of a Previously Developed Geospatial Model That Predicts the Prevalence of Listeria monocytogenes in New York State Produce Fields. Appl Environ Microbiol. 2016;82:797-807.

[23] Allard MW, Strain E, Melka D, Bunning K, Musser SM, Brown EW, Timme R. Practical Value of Food Pathogen Traceability through Building a Whole-Genome Sequencing Network and Database. J Clin Microbiol. 2016;54:1975-83.

[24] den Bakker HC, Moreno Switt AI, Govoni G, Cummings CA, Ranieri ML, Degoricija L, et al. Genome sequencing reveals diversification of virulence factor content and possible host adaptation in distinct subpopulations of Salmonella enterica. BMC Genomics. 2011;12:425.

[25] Gilmour MW, Graham M, Van Domselaar G, Tyler S, Kent H, Trout-Yakel KM, et al. High-throughput genome sequencing of two Listeria monocytogenes clinical isolates during a large foodborne outbreak. BMC Genomics. 2010;11:120.

[26] Grande L, Michelacci V, Bondi R, Gigliucci F, Franz E, Badouei MA, et al. Whole-Genome Characterization and Strain Comparison of VT2f-Producing Escherichia coli Causing Hemolytic Uremic Syndrome. Emerg Infect Dis. 2016;22:2078-86.

[27] Lindsey RL, Pouseele H, Chen JC, Strockbine NA, Carleton HA. Implementation of Whole Genome Sequencing (WGS) for Identification and Characterization of Shiga Toxin-Producing Escherichia coli (STEC) in the United States. Front Microbiol. 2016;7:766.

[28] Kovac J, Miller RA, Carroll LM, Kent DJ, Jian J, Beno SM, Wiedmann M. Production of hemolysin BL by Bacillus cereus group isolates of dairy origin is associated with whole-genome phylogenetic clade. BMC Genomics. 2016;17:581.

[29] Nieuwenhuijse DF, Koopmans MP. Metagenomic Sequencing for Surveillance of Food- and Waterborne Viral Diseases. Front Microbiol. 2017;8:230.

[30] Ottesen AR, Gonzalez A, Bell R, Arce C, Rideout S, Allard M, et al. Co-enriching microflora associated with culture based methods to detect Salmonella from tomato phyllosphere. PLoS One. 2013;8.

[31] Yang X, Noyes NR, Doster E, Martin JN, Linke LM, Magnuson RJ, et al. Use of Metagenomic Shotgun Sequencing Technology To Detect Foodborne Pathogens within the Microbiome of the Beef Production Chain. Appl Environ Microbiol. 2016;82:2433-43.

[32] Katz LS, Petkau A, Beaulaurier J, Tyler S, Antonova ES, Turnsek MA, et al. Evolutionary dynamics of Vibrio cholerae O1 following a single-source introduction to Haiti. MBio. 2013;4.

[33] Morelli G, Song Y, Mazzoni CJ, Eppinger M, Roumagnac P, Wagner DM, et al. Yersinia pestis genome sequencing identifies patterns of global phylogenetic diversity. Nat Genet. 2010;42:1140-3.

[34] Loman NJ, Misra RV, Dallman TJ, Constantinidou C, Gharbia SE, Wain J, Pallen MJ. Performance comparison of benchtop high-throughput sequencing platforms. Nat Biotechnol. 2012;30:434-9.

[35] Gilmour MW, Graham M, Van Domselaar G, Tyler S, Kent H, Trout-Yakel KM, et al. High-throughput genome sequencing of two Listeria monocytogenes clinical isolates during a large foodborne outbreak. BMC Genomics. 2010;11:120.

[36] Lienau EK, Strain E, Wang C, Zheng J, Ottesen AR, Keys CE, et al. Identification of a salmonellosis outbreak by means of molecular sequencing. N Engl J Med. 2011;364(10):981-2. doi:10.1056/NEJMc1100443.

[37] Sena-Torralba A, Pallás-Tamarit Y, Morais S, Maquieira Á. Recent advances and challenges in food-borne allergen detection. TrAC Trends Anal Chem. 2020;132:116050. doi:10.1016/j.trac.2020.116050.

[38] Zahran D, Hagag S. Use of molecular biology techniques in the detection of fraud meat in the Egyptian market. Afr J Biotechnol. 2015;14(5):360-4. doi:10.5897/AJB2014.14297.

[39] Kesmen Z, Büyükkiraz ME, Kahraman N, Yetim H. Detection of fraudulent practices involving some plant derived compounds in foods using real-time PCR. J Food. 2017;42(3):305-14. doi:10.15237/gida.GD16110.

[40] Böhme K, Calo-Mata P, Barros-Velazquez J, Ortea I. Review of recent DNA-based methods for main food-authentication topics. J Agric Food Chem. 2019;67:3854-64. doi:10.1021/acs.jafc.8b07016.

[41] Kabacaoğlu E, Karakaş BB. Detection and quantification of salep with real time PCR utilizing the nrITS2 region. J Sci Food Agric. 2019;99:2447-54. doi:10.1002/jsfa.9453.

[42] Sobrino-Gregorio L, Vilanova S, Prohens J, Escriche I. Detection of honey adulteration by conventional and real-time PCR. Food Control. 2019;95:57-62. doi:10.1016/j.foodcont.2018.07.037.

[43] Villa C, Costa J, Oliveira BM, Mafra I. Novel quantitative real-time PCR approach to determine safflower (Carthamus tinctorius) adulteration in saffron (Crocus sativus). Food Chem. 2017;229:680-7. doi:10.1016/j.foodchem.2017.02.136.

[44] Castillo DS, Cassola A. Novel sensitive monoclonal antibody based competitive enzyme-linked immunosorbent assay for the detection of raw and processed bovine beta-casein. PLoS One. 2017;12(7). doi:10.1371/journal.pone.0182447.

[45] Sena-Torralba A, Pallás-Tamarit Y, Morais S, Maquieira Á. Recent advances and challenges in food-borne allergen detection. TrAC Trends Anal Chem. 2020;132:116050. doi:10.1016/j.trac.2020.116050.

[46] Panda R, Garber EA. Western blot analysis of fermented-hydrolyzed foods utilizing gluten-specific antibodies employed in a novel multiplex competitive ELISA. Anal Bioanal Chem. 2019;411:5159-74. doi:10.1007/s00216-019-02142-8.

[47] Lata K, Sharma R. Lateral flow assay concept and its applications in food analysis. Lateral. 2013;32(5).

[48] Gbashi S, Adebo O, Adebiyi A, Targuma S, Tebele SO, Areo OM, et al. Food safety, food security and genetically modified organisms in Africa: a current perspective. Biotechnol Genet Eng Rev. 2021. doi:10.1080/02648725.2021.1940735.

[49] Jans C, Meile L, Kaindi DWM, Kogi-Makau W, Lamuka P, Renault P, et al. African fermented dairy products - Overview of predominant technologically important

microorganisms focusing on African Streptococcus infantarius variants and potential future applications for enhanced food safety and security. Int J Food Microbiol. 2017;250:27-36. doi:10.1016/j.ijfoodmicro.2017.03.012.

[50] Aryee SND, Owusu Adjei D, Osei Amponsah R, Skinner B, Sowatey E, Sargent CA. Sustainable genomic research for food security in Sub-Saharan Africa. Agric Food Sec. 2021;10:8. doi:10.1186/s40066-021-00287-9.

[51] Obidiegwu CS, Chineke HN, Ubajaka CN, Adogou POU. Public health challenges in Somachi Main Abattoir Owerri, Nigeria: A review and field activity report. Somachi. 2019;1:1-7.

[52] Dapuliga CC, Gadafi IB, Okareh OT, Richard O, Mohammed T. Food safety in Sub-Saharan Africa: An insight into Ghana and Nigeria. Environ Health Insights. 2022;16:1-18. doi:10.1177/11786302221142484.

[53] Rybicki EP, Hitzeroth II, Meyers A, Dus Santos MJ, Wigdorovitz A. Developing country applications of molecular farming: case studies in South Africa and Argentina. Curr Pharm Des. 2013;19(31):5612-21. doi:10.2174/1381612811319310015.

[54] Arthur G, Yobo K. Genetically modified crops in Africa. In: Ahuja M, Ramawat K, editors. Biotechnology and Biodiversity. Sustainable Development and Biodiversity. Vol. 4. Cham: Springer; 2014. p. 35-50. doi:10.1007/978-3-319-09381-9_2.

[55] Black R, Fava F, Mattei N, Robert V, Seal S, Verdier V. Case studies on the use of biotechnologies and on biosafety provisions in four African countries. J Biotechnol. 2011. doi:10.1016/j.jbiotec.2011.06.036.

[56] Keese PK, Robold AV, Myers RC, Weisman S, Smith J. Applying a weed risk assessment approach to GM crops. Transgenic Res. 2013. doi:10.1007/s11248-013-9745-0.

[57] Johnson KL, Raybould AF, Hudson MD, Poppy GM. How does scientific risk assessment of GM crops fit within the wider risk analysis? Trends Plant Sci. 2007;12:1-5.

[58] Bennett R, Phipps R, Strange A, Grey P. Environmental and human health impacts of growing genetically modified herbicide-tolerant sugar beet: a life-cycle assessment. Plant Biotechnol J. 2004;2:273-8.

[59] Manjeru P, Van Biljon A, Labuschagne M. The development and release of maize fortified with provitamin A carotenoids in developing countries. Crit Rev Food Sci Nutr. 2019;59:1284-93. doi:10.1080/10408398.2017.1402751.

[60] Michel V, Julio E, Candresse T, Cotucheau J, Decorps C, Volpatti R, et al. A complex eIF4E locus impacts the durability of Va resistance to Potato virus Y in tobacco. Mol Plant Pathol. 2019;20(8):1051-66. doi:10.1111/mpp.12782.

[61] Gomez MA, Lin ZD, Moll T, Chauhan RD, Hayden L, Renninger K, et al. Simultaneous CRISPR/Cas9-mediated editing of cassava eIF4E isoforms nCBP-1 and nCBP-2 reduces cassava brown streak disease symptom severity and incidence. Plant Biotechnol J. 2019;17(2):421-34. doi:10.1111/pbi.13009.

[62] Macovei A, Sevilla NR, Cantos C, Jonson GB, Slamet-Loedin I, Čermák T, et al. Novel alleles of rice eIF4G generated by CRISPR/Cas9-targeted mutagenesis confer resistance to Rice tungro spherical virus. Plant Biotechnol J. 2018;16(11):1918-27. doi:10.1111/pbi.12930.

[63] Tripathi L, Ntui VO, Tripathi JN. Application of genetic modification and genome editing for developing climate-smart banana. Food Energy Sec. 2019;8(4). doi:10.1002/fes3.168.

[64] Syombua ED, Tripathi JN, Obiero GO, Nguu EK, Yang B, Wang K, Tripathi L. Potential applications of the CRISPR/Cas technology for genetic improvement of yam (Dioscorea spp.). Food Energy Sec. 2022;11(1). doi:10.1002/fes3.330.

[65] Amusa NA, Adigbite AA, Muhammed S, Baiyewu RA. Yam diseases and its management in Nigeria. Afr J Biotechnol. 2003;2(12):497-502.

[66] Sameeullah M, Khan FA, Özer G, Aslam N, Gurel E, Waheed MT, Karadeniz T. CRISPR/Cas9-mediated immunity in plants against pathogens. Curr Issues Mol Biol. 2018;26(1):55-64. doi:10.21775/cimb.026.055.

[67] Naidoo T. Making safe food a reality: safety & hygiene. Food Manuf Africa. 2016;4(2):16.

[68] Mulder NJ, Adebiyi E, Adebiyi M, Adeyemi S, Ahmed A, Ahmed R, Akanle B, Alibi M, Armstrong DL, Aron S, et al. Development of bioinformatics infrastructure for genomics research. Glob Heart. 2017;12:91-8. doi:10.1016/j.gheart.2017.01.002.

[69] Chukwudi CU. Consolidating and upscaling molecular research capacity in Nigeria: On whose account? Front Res Metrics Anal. 2022;6:788673. doi:10.3389/frma.2021.788673.

[70] Luka PD, Erume J, Mwiine FN, Ayebazibwe C, Shamaki D. Molecular characterization and phylogenetic study of peste des petits ruminants viruses from North Central States of Nigeria. BMC Vet Res. 2011;7:32. doi:10.1186/1746-6148-7-32.

[71] Nwagbo IO, Shittu I, Nwosuh CI, Ezeifeka GO, Odibo FJC, Michel LO. Molecular characterization of field infectious bursal disease virus isolates from Nigeria. Vet World. 2016;9:1420. doi:10.14202/vetworld.2016.1420-1428.

[72] Ugochukwu IC, Ikem CF, Chukwudi CU. Comparative clinical, histopathological and molecular approaches for PPR diagnosis in naturally infected West African Dwarf (WAD) goats. J Vet Sci Med Diagn. 2021;10:1000297. doi:10.4172/2325-9590.1000297.

[73] Folarin OA, Happi AN, Happi CT. Empowering African genomics for infectious disease control. Genome Biol. 2014;15:515. doi:10.1186/s13059-014-0515-y.

[74] Maxmen A. The next chapter for African genomics. Nature. 2021;578:350-4. doi:10.1038/d41586-020-00454-1.