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Assessing the Impact of New Agricultural Technologies on Food Safety in Sub-Saharan Africa

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ABSTRACT

The agricultural sector has been focused on meeting the nutritional needs of the growing world population, but it faces numerous challenges including increased climate change, urbanisation, and environmental degradation. Innovative technologies used in the agricultural sector to meet these needs include genetically modified organisms, nanotechnology, and vertical farming. However, there are concerns surrounding these new technologies, such as their effects on the environment and health of the populace. African countries cultivating genetically modified crops have implemented regulatory frameworks and risk assessments to address these concerns. Nanotechnology raises concerns about the migration of nanoparticles into food, necessitating the development of specific regulations. Aquaculture carries risks of pathogenic microorganisms and antimicrobial residues. This article discusses the effect of these emerging technologies on food safety in Sub-Saharan Africa and emphasises the need to address the challenges faced with managing these technologies and opportunities to address the risks associated with them.

1 | Introduction

Meeting the nutritional needs of the people has been the main objective of agricultural practices over the years. According to the United Nations prediction, by 2030, the world population could be around 8.5 billion in 2030 and about 10.4 billion in 2100, with the population of sub-Saharan African countries almost doubling, surpassing the 2 billion inhabitants by the late 2040s [1]. Coping with the ever-increasing number of people has been a challenge to the agricultural sector over time. Alongside the increase in population resulting from a higher fertility rate, increased life longevity, significant disparities in old versus young people, changes in climate, rapid urbanisation, and environmental degradation are factors affecting agricultural outputs [2]. The current agricultural system may not be able to cater to future needs.

Modern methods in biotechnology have experienced significant development aimed at improving the existing food systems. In developing countries including Sub-Saharan Africa, the agricultural development agendas are shaped by a focus on advanced technologies that include genetically modified (GM) crops, vertical farming, and nanotechnology. Although these techniques are promising agricultural interventions to

Summary

- Emerging agricultural technologies offer solutions to food security challenges but introduce new food safety risks such as allergenicity, antimicrobial residues, and nanoparticle migration.
- Regulatory frameworks in Sub-Saharan Africa remain inconsistent and often fail to address the unique challenges posed by new technologies, necessitating stronger policies and enforcement mechanisms.
- Stakeholder collaboration, investment in research, and public awareness initiatives are essential for mitigating food safety risks and ensuring sustainable agricultural development.

slow down the rate of food insecurity in Africa, there is a strong counterview from different researchers on their potential benefits and hazards. For example, there are speculations surrounding the adoption of GMOs, especially its effects on the environment, ethical issues, and food safety even in the face of their numerous benefits such as improved yields and resistance to diseases in tackling the current situation in Africa [3].

Despite ongoing efforts by the authorities and regional agencies to improve the situation, food safety and security in Africa remain critical. According to the [4] report on undernourishment, Africa is the worst-hit region in percentage terms, with about 250 million Africans believed to be undernourished based on a UN assessment.

Food security is the uninterrupted access to sufficient, safe, and nutritious food to maintain a healthy and active life [5]. In the United Nations 2030 Agenda, food security, an important factor in its sustainable development goals (SDGs), does not only mean the production of adequate food that is accessible to all, but it is also essential that all consumed food is safe and meets the required nutrient demand. In summary, there is no food security without food safety. Although this does not diminish the need for the availability of food in sufficient quantities and appropriate quality, a lack of safety and poor food quality undoubtedly contribute to the continent's current food insecurity crisis. Food can contain a variety of biological and chemical risks, including allergies, pesticides, mycotoxins, antimicrobial residues, and pathogenic microorganisms [3]. According to [6], many of these detected food safety hazards, including viruses and fungal toxins, are farm-based and one of the major factors suspected is the undermining of quality agricultural products in Africa.

Access to safe and nutritious food is a human right. To meet the continent's food demand, the African agricultural sector needs to undergo a tremendous innovative change while at the same time maintaining a public health standard that addresses the vulnerable. Also, a diversified method that ensures food safety without raising the environmental footprint must be employed. This paper, therefore, highlights the impact of emerging agricultural technologies on food safety in Sub-Saharan Africa.

2 | New Agricultural Technologies and Food Safety Risks

2.1 | Genetically Modified Organisms (GMOs)

GMOs are living organisms whose genetic material has been altered unnaturally by gene recombination or mating through genetic engineering techniques [7]. This involves the addition of a gene or trait from one organism to another to produce desired traits or characteristics [8]. For example, in the agricultural sector, there are certain crops engineered to exhibit traits that make them resist pests, diseases, adverse environmental conditions, etc. They are also modified to enhance their nutritional value [3]. For example, herbicide-tolerant soybeans are widely cultivated in South Africa, significantly enhancing commercial soybean production. GM cassava is under extensive research in Kenya, Nigeria, and Uganda for its potential to resist devastating viruses [9]. Bt cotton, cultivated in many parts of the continent, provides resistance to pests and has led to improved yields. Ultimately, South Africa still stands out as a leader, with over 80% of its maize, soybean, and cotton crops genetically modified, resulting in yield increases of up to 50%. Nigeria has made remarkable progress with the introduction of Bt cowpea, which targets the Maruca pod borer, a pest responsible for up to 80% of crop losses. Recently, Kenya lifted its ban on GMOs, enabling trials of Bt maize [10]. GM crops are cheaper to grow as they require less pesticides, which also reduces the amount of carbon dioxide that is released into the atmosphere when compared to conventional crops [11]. They also contribute to the conservation of natural resources by reducing the need for water, pesticides, and fertilisers.

There are growing concerns about the impacts of GM crops regarding the socio-economic, health, and the environment [11–13], despite these advancements. A study by Azadi and Ho [14] shows that the major environmental concern with GM crops is the decrease in biodiversity, as their introduction into the ecosystem could have unintended consequences. Additionally, GM crops may also have adverse health effects such as the transfer of antibiotic-resistance genes, toxicity, and allergenicity [12]. C. Zhang et al. [15] explored the health implications of GM foods in their study and suggested that GM foods may unintentionally introduce new allergens or increase the levels of existing allergenic substances in food crops. Other studies suggest that GM foods may cause common toxic effects such as pancreatic, hepatic, renal, or reproductive effects and disrupt the biochemical, haematological, and immunologic parameters [16]. Using antibiotic-resistance genes as marker genes during the genetic modification of foods can further contribute to the development of antibiotic-resistant bacteria, which reduces the effectiveness of antibiotics in treating human and animal diseases.

These environmental and health risks associated with GMOs emphasise the need to implement comprehensive regulatory frameworks and conduct thorough risk assessments before genetically modified crops are fully adopted in Africa.

African countries cultivating GM foods, such as South Africa, Kenya, Malawi, and Nigeria, have implemented robust regulatory frameworks to address food safety concerns [17]. Rigorous risk assessments are conducted to evaluate potential risks, including allergenicity and toxicity [18]. Labelling requirements provide transparency and enable consumers to make informed choices. The African Union Commission has also contributed to biosafety guidelines with the African Model Law on Biosafety, developed in 2003 and revised in 2009, along with the African Biosafety Strategy [19]. These initiatives aim to balance innovation, food security, and public health while providing consumers with information for informed decision-making. Through these measures, African countries strive to ensure the safety of GM crops and address food safety concerns effectively.

Figure 1 highlights important years in the development of food safety regulations across Africa, showing important events and initiatives that are aimed at improving food safety standards, biosafety management and regulatory frameworks.

2.2 | Nanotechnology

The National Institute for Occupational Safety and Health (NIOSH) defines nanotechnology as the manipulation of matter on the near-atomic scale, typically in the range of 1–100 nm to produce new materials or structures [20]. At this tiny size, the materials exhibit unique properties and behaviours that can be used for various applications. It offers opportunities to develop innovative products and applications in the agriculture and food sectors. There are significant investments from governments, industries, and science in its application to food production [21]. Examples of nanotechnology used in the food sector include nanoparticles that can be used as antimicrobial agents in packaging materials such as silver nanoparticles (AgNPs). Titanium dioxide (TiO_2) is also commonly used as a food additive for brightening. Another example of nanotechnology used in the food sector is Zinc oxide (ZnO), which is used to coat packaging materials for UV protection and antimicrobial effects [22]. Nanosensors are also used in detecting contaminants or pathogens in food, therefore ensuring safety and minimising the risk of foodborne illnesses [23] and nanoemulsions can improve the delivery and absorption of nutrients, enhancing the bioavailability of vitamins and minerals [24]. Nanomaterials can be used to extend the shelf life of perishable products [25]. They are encouraged in several regions of the continents such as the South African Nanotechnology Initiative (SANi), which promotes the use of nanotechnology in food and agriculture. There is also the Nanoscience Africa Network that engages in regional research collaborations in agriculture and food safety. Nigeria and Kenya are also exploring nanotechnology applications, though commercialisation remains limited [26].

However, the use of these nanotechnologies in food poses concern about their potential risks to human health. Nanoparticles can migrate from the food packaging into the food itself. This is one of the primary food safety risks associated with nanotechnology [27]. These nanoparticles could then be ingested and have unknown effects on human health. When there is long-term exposure via food, their effects on the gut microbiome should be assessed in terms of their risk to human health, especially when a nanomaterial exhibits antimicrobial properties [28].

The regulations and policies regarding nanotechnology are still in Africa's early stages of development. Most African countries have not yet formed specific regulations that focus solely on nanotechnology but still rely on existing food safety regulations that may not address the unique challenges posed by nanomaterials adequately.

However, a few countries like South Africa and Egypt have made some progress in establishing regulatory frameworks for nanotechnology. However, harmonisation and coordination among African nations regarding nanotechnology regulation

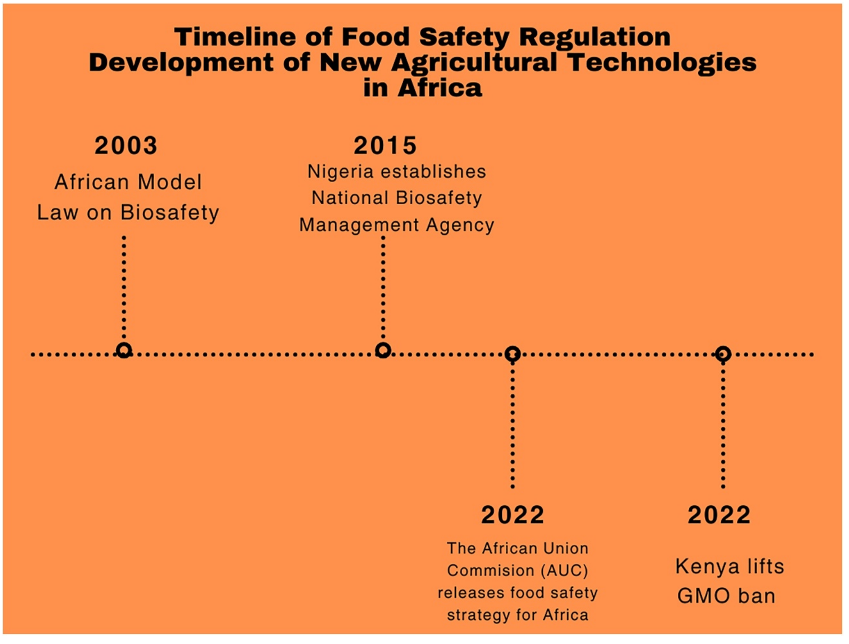

FIGURE 1 | Key milestones in food safety regulations in Africa.

remain limited. Collaborative efforts and knowledge-sharing platforms should be encouraged to facilitate the development of effective regulations that will ensure the use of nanotechnology in the food industry throughout Africa.

2.3 | Aquaculture

Aquaculture is the practice of growing seafood and seafood products. It is the fastest-growing food sector that has contributed significantly to the realisation of SDGs 1, 2, 5 & 8 [29]. Aquaculture is categorised into two categories: fish hatchery and Pond culture. Fish hatchery entails the production of fingerlings, while pond culture involves the use of earthen ponds and the construction of concrete tanks for aquaculture production [30].

Aquaculture is rapidly expanding in Ghana, Kenya, and Uganda. Ghana produces over 60,000 tons of fish annually, while Kenya and Uganda are investing in cage farming in Lake Victoria.

However, seafood is a rich component of the human diet that can carry a variety of pathogenic microorganisms that pose threats to public health. For example, shellfish harbours *Vibrio* bacterium, *Escherichia coli*, etc., and have been implicated in causing human gastroenteritis associated with the consumption of contaminated seafood [31, 32]. Chemical additives such as antibiotics used as growth promoters could accumulate antimicrobial residues in seafood tissues [33, 34].

Aquaculture regulations vary from country to country in Africa. For example, the Federal Department of Fisheries regulates and sets policies promoting sustainable aquaculture practices in Nigeria [29, 36]. In Egypt, The Ministry of Agriculture and Land Reclamation is responsible for planning, managing, and controlling all activities concerning fish production [37, 38].

2.4 | Vertical Farming

Vertical farming, as a soil less, climate resilience urban farming technology, involves growing crops in a controlled environment. Vertical farming fosters food security and climate adaptability [39]. There are three types of vertical farms: hydroponics, aeroponics, and aquaponics. Hydroponics is the most common system used in vertical farms. It involves growing plants in a nutrient-rich solution containing all the necessary growth requirements rather than soil. Aeroponic involves growing plants in an air medium with limited water without the use of soil [40]. On the other hand, Aquaponics integrates aquaculture and hydroponic systems. The nutrient-rich water from a fish tank serves as a source of nutrients for the plants, and the plants, in turn, detoxify the water [41].

Food safety concerns associated with vertical farming are common to an aquaponic system. The use of untreated fish wastewater has the potential to contaminate plants with pathogenic organisms like *E. coli* and *Salmonella* and affect the safety of plants for consumption. As well as introduce chemical residue from pesticides and contaminants from fish feed into aquaponic systems, which can accumulate in plant tissues and ultimately affect public health.

Vertical farming in Africa as an emerging technology is relatively new. Policy prescriptions defer from one country to another.

In Namibia, The Ministry of Agriculture, Water and Forestry fosters agricultural practices towards food security by improving access to quality fresh agro-products at the household level all year round [42]. In Nigeria, the Agriculture Promotion Policy developed initiatives that focus on food security, import substitution, job creation, and economic diversification [43].

Figure 2 and Table 1 summarises these emerging agricultural technologies and the food safety risks associated with them.

3 | Challenges Associated With Emerging Agricultural Technologies and Their Food Safety Risks in Africa

3.1 | Inadequate Regulations and Policies

Inadequate regulations and policies regarding food safety in African countries pose significant challenges in ensuring the quality and safety of food products.

One major issue is the lack of comprehensive and harmonised regulations specific to emerging agricultural technologies. While some African countries such as South Africa, Nigeria, Sudan, Egypt, Burkina Faso, etc have made progress in establishing regulatory frameworks for genetically modified organisms (GMOs), others such as Kenya, Tanzania, Uganda, etc. still have little or no information regarding GMOs [44]. This inconsistency creates uncertainty and hampers the adoption and safe use of these technologies. This regulatory gap increases the risk of food contamination and public health concerns (Table 2). Additionally, the regulatory frameworks often fail to keep pace with advancements in agricultural technologies. This lag can result in outdated regulations that do not adequately address the potential risks associated with emerging technologies such as nanotechnology and aquaculture.

Table 3 provides an overview of food safety regulations in Sub-Saharan Africa, highlighting varying policies across countries related to GMOs, nanotechnology, aquaculture and vertical farming.

3.2 | Weak Enforcement of Existing Regulations

Even in countries where food safety laws exist, enforcement remains a significant challenge.

Africa continues to have the worst food safety records when compared to other continents, and 30% of foodborne illness-related deaths worldwide occur there. The highest estimates worldwide attribute consumption of unsafe food to roughly

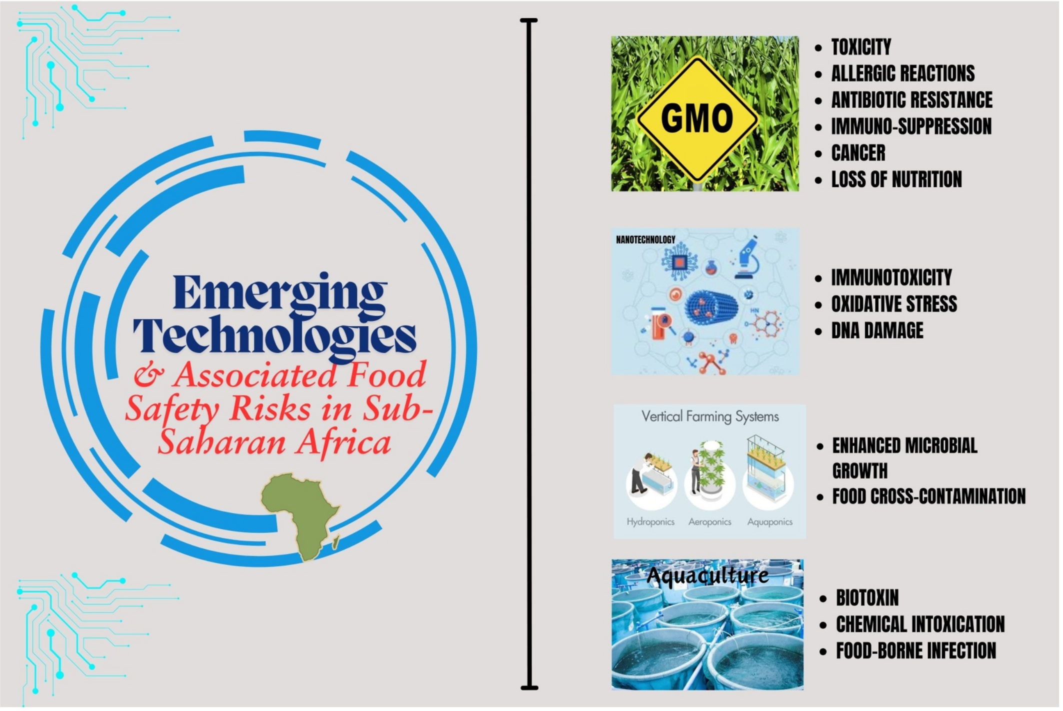

FIGURE 2 | Emerging agricultural technologies and food safety risks associated with them in SSA. Genetically Modified Organisms (GMOs): Benefits include higher yields and pest resistance, but risks include allergenicity and gene transfer. Nanotechnology: Used in food packaging and nutrient delivery, yet migration of nanoparticles into food remains a safety concern. Vertical Farming: Provides climate-resilient solutions but faces challenges in water contamination and pesticide residues. Aquaculture: Expanding rapidly but raises concerns about antimicrobial residues and pathogen contamination.

TABLE 1 | Summary of emerging agricultural technologies and associated risks.

Technology	Key applications	Food safety risks	Examples in sub-Saharan Africa
Genetically modified organisms (GMOs)	Pest resistance, higher yields	Allergenicity, gene transfer, biodiversity loss	Bt cowpea in Nigeria, GM maize in South Africa
Nanotechnology	Food packaging, nutrient delivery	Migration of nanoparticles into food	Zinc oxide in packaging (South Africa)
Aquaculture	Fish farming, pond culture	Pathogens (e.g., *Vibrio*), antimicrobial residues	Cage farming in Kenya, fish farming in Ghana
Vertical farming	Hydroponics, aquaponics	Contaminants from untreated water	Urban hydroponics in Nigeria and Kenya

TABLE 2 | Gaps and opportunities for emerging technologies.

Area	Current gaps	Opportunities
Regulation	Lack of harmonised policies	Regional frameworks for food safety
Technology adoption	Limited access to modern technologies	Subsidies for smallholder farmers
Research and development	Early-stage nanotechnology research	Public-private partnerships for R&D
Public awareness	Misconceptions about food safety risks	Awareness campaigns targeting rural areas

137,000 fatalities and 91 million cases of acute foodborne illnesses each year in Africa. The absence of strict monitoring mechanisms allows the continued circulation of contaminated food, leading to widespread foodborne illnesses. In Africa, few studies have examined the safety of the production chain while many have examined food contamination at the consumption level [45]. Governments have limited capacity for regulatory enforcement and inspections. Private food safety audit firms and independent food testing laboratories are also uncommon. A major contributor to food contamination, particularly at the consumption level, is inadequate education. As a result, consumers and policymakers tend to pay less attention to safety [45, 46]. For example, Nigeria records over 200,000 cases of foodborne illness annually, with mycotoxin contamination in maize and groundnuts being a

TABLE 3 | Food safety regulations in Sub-Saharan Africa.

Country	GMO regulations	Nanotechnology policies	Aquaculture standards	Vertical farming guidelines
Nigeria	Established biosafety Act	No dedicated policies	Federal aquaculture guidelines	Limited regulations
Kenya	GMO trials ongoing	Initial nanotech frameworks	Fish Act covers aquaculture	Urban farming initiatives
Ghana	Limited GMO policies	No active frameworks	No active frameworks policies for sustainable aquaculture	No specific policies
South Africa	Comprehensive (biosafety Act)	Early-stage labelling policies	Well-regulated, clear standards	Emerging focus

significant health threat [47–49]. A study by ref. [50] showed that fumonisins contaminated all the maize and groundnut/maize-based snacks in Nigeria, with higher concentrations in the maize-based snacks (mean = 218.7 $\mu g\ kg^{-1}$). Aflatoxins were also detected in these snacks, with some exceeding the National Agency for Food and Drug Administration and Control (NAFDAC) recommended limit of 20 $\mu g\ kg^{-1}$. Similarly, South Africa has faced major *Listeria* outbreaks; in 2017–2018, the outbreak resulted in 1065 confirmed cases and 218 deaths [51]. These statistics highlight the urgent need for better food safety enforcement. Unfortunately, the majority of the countries in Africa lack effective food safety systems that are strong enough to adequately protect consumer health and boost the competitiveness of food exports. Food safety systems are weak, fragmented and poorly coordinated. However, it is acknowledged that enhancing food safety systems can be expensive in both the short and long term and difficult for many nations to implement.

3.3 | Regulating Food Markets in Africa

In terms of regulating the food markets in Africa, few studies focused on regulatory policies have been carried out [52]. Several studies show that foods sold in outdoor food markets in Africa are often prone to food contamination caused by several pathogens. In Nigeria, street-vended foods have been found to harbour harmful bacteria. A study by ref. [53], analysed ready-to-eat foods sold in Yenagoa, Bayelsa State, Nigeria, detected various pathogenic strains of *Escherichia coli*, including atypical enterotoxigenic, enteroaggregative, enteropathogenic, and enteroinvasive strains, concluded that some ready-to-eat foods sold in the area are contaminated and pose a probable human health hazard. In Uganda, Studies show that 30%–50% of fresh produce in open-air markets is contaminated with mycotoxins, which are secondary fungal metabolites with the potential to harm both humans [54].

The challenge is further compounded by the lack of regular inspections. While supermarkets and formal retail chains have stricter food safety policies, informal vendors, who account for over 70% of food sales in Africa, are often unregulated. Many governments struggle to monitor these markets, leading to widespread food safety violations. Without improved oversight and food hygiene education, foodborne illness outbreaks will remain prevalent.

4 | Strategies for Addressing Food Safety Risks In Sub-Sahara Africa

4.1 | Collaboration and Partnership Among Stakeholders

Collaboration and partnership among stakeholders, particularly between government bodies and private organisations, play a crucial role in addressing the food safety risks associated with implementing new agricultural technologies in Africa. Many countries still lack harmonised policies to regulate food safety risks associated with emerging agricultural technologies (Table 2).

By working together, these bodies can leverage their expertise, resources, and networks to tackle the challenges effectively and ensure the safety of the food supply chain. One notable example of collaboration is the partnership between the West Africa Agricultural Productivity Program (WAAPP) and various stakeholders. WAAPP works to generate and disseminate improved agricultural technologies in priority areas by the Central Africa Council for Agricultural Research (CORAF) including cereals in Senegal, roots and tubers in Ghana, and rice in Mali [55]. Through this programme, researchers, extension agencies, and universities collaborate to develop and promote technology-supported solutions. By involving both public and private entities, the programme ensures a comprehensive approach to addressing food safety risks. Additionally, regional cooperation is facilitated through the standardisation of regulations and the development of information systems. At the Economic Community of West African States (ECOWAS) level, common regulations for genetic material, pesticides, and crop protection products have been established [55]. This harmonisation enables easier exchange of technologies and knowledge across borders. Additionally, a regional agriculture technology and research skills information system is developed to facilitate the sharing of information and best practices among stakeholders. Various NGOs and international organisations also play a significant role in addressing food safety risks in Africa. For example, the Food and Agriculture Organization (FAO), the World Health Organization (WHO), and local NGOs such as the African Food Safety Network (AFoSAN) also contribute to addressing food safety risks. These organisations work closely with communities, advocating for improved food safety policies, conducting research, and raising awareness about the importance of safe food production and consumption.

A South African study found that stakeholders' collaboration and partnerships are needed in the food retail sector to improve food safety and prevent risks [56].

Collaboration among stakeholders is very important, but where the real challenge is on getting this collaboration to operate effectively.

Below are the suggested steps for creating functional partnerships that will ensure that every stakeholder plays an important role in achieving the intended outcomes.

i. Identifying Key Stakeholders: The stakeholders involved in agricultural development must include a diverse array of participants such as Government agencies which include local agricultural boards, national ministries of agriculture, and policy-makers responsible for crafting and implementing agricultural regulations and funding opportunities [57], agricultural extension services like local extension officers who serve as the primary touchpoints between farmers and technological innovations, farmers' association that provide a collective voice for farmers, advocating for their needs and ensuring equitable access to resources, research institutions such as universities and agricultural research centres can support evidence-based solutions for technology and farming best practices. Also, private sector partners (Agri-tech companies) that will provide technologies, digital tools, and innovation necessary for modernising agriculture, and NGOs that are focused on capacity-building, will ensure farmers receive the necessary training and support, especially in rural or underserved regions.

ii. Appointing a Central Coordinating Body: A central body is critical to efforts. A regional agricultural board can serve as this entity that coordinates resources and ensures that all stakeholders are aligned. This body should be structured similarly to successful examples in Africa and Asia, where regional hubs led by multi-stakeholder consortia oversee agricultural development [58].

iii. Creating Memoranda of Understanding (MoUs): To formalise collaboration, MoUs should be drafted to establish roles, responsibilities, and accountability structures for all parties. These agreements can outline specific areas of responsibility, such as funding sources, technical expertise, or farmer outreach [59].

iv. Establishing Regular Communication Channels: Platforms like WhatsApp, Zoom, or dedicated mobile apps should be leveraged for real-time information sharing to prevent miscommunication and to ensure consistency; regular stakeholder forums both physical and virtual are important. [60]. Such communication allows for immediate feedback loops and adjustment of strategies as needed.

4.2 | Investment in Research and Development

Investment in food safety R&D in Africa involves significant contributions from governments, international organisations, research institutions, and the private sector. As highlighted in Table 2, nanotechnology research in Africa is still at an early stage, which limits its potential in improving food safety. Governments allocate funds to support regulatory frameworks, scientific studies and monitoring systems, which will result in improved standards and compliance. International organisations like WHO, FAO, and the AU provide technical expertise, training, and financial support to strengthen food safety systems and promote collaboration. Research institutions focus on various areas and contribute to innovative technologies, testing methods, and evidence-based policies. The private sector invests in quality control systems, testing, and traceability to meet regulatory requirements and consumer demands.

However, to effectively persuade farmers to adopt these innovative technologies, it is important to;

i. Set up demonstration farms where innovative technologies can be showcased is a proven method for persuading farmers to adopt new practices. These pilot programs offer farmers a low-risk opportunity to see the benefits of technology firsthand [61]. Success stories from peer farmers play a powerful role in promoting uptake.

ii. Introduce financial incentives that will offset the initial costs associated with technology adoption. Governments and private sector partners can provide low-interest loans, equipment discounts, or subsidy programs targeted at smallholder farmers [62]. Moreover, crop insurance schemes tied to technology usage could mitigate the perceived financial risks of adopting new methods.

iii. Set up Peer-to-Peer Learning Networks. Farmers are more likely to adopt new technologies when they can learn from their peers. Organising farmer field schools or peer learning networks has been shown to significantly boost adoption rates, as it builds trust and reduces the intimidation often associated with high-tech innovations [63]. These networks can also act as informal support groups for troubleshooting and problem-solving.

iv. Ensure farmers are trained to understand how to use new tools. In addition to traditional on-site training through extension services, remote training options such as mobile phone-based modules and video tutorials should be available. Studies from Kenya and India have shown that such digital platforms are particularly effective in reaching remote areas [64].

v. Establish support centres, either operated by NGOs or private agri-tech companies, that offer continuous technical support. These centres would provide ongoing assistance, particularly in the early stages of technology adoption. The success of this approach has been noted in several Sub-Saharan African countries where technical support teams provided by companies such as Hello Tractor have drastically improved the implementation of new technologies [65].

vi. Develop behavioural economics that can be used to develop persuasive messaging that emphasises immediate benefits and long-term gains. Farmers are more likely to adopt innovations if they are framed in ways that resonate with their goals—improving yields, reducing labour, or securing long-term sustainability. This approach has been successfully used in Rwanda to increase fertiliser usage among smallholder farmers [66].

Overall, the collective efforts of the major actors have a positive impact on enhancing food safety standards, building capacity, and protecting the health of Africans.

4.3 | Adoption of Innovative Technologies for Food Safety Management

To meet the demand of the ever-increasing population, evolving technologies have been created and implemented to produce all types of foods, including foods derived from contemporary biotechnology. For instance, the West Africa Agricultural Productivity Program (WAAPP), which concentrates on the top agricultural priorities of each nation, works to support agricultural technology research and extension in Ghana, Mali, and Senegal [55]. Today, the food supply of the African region is threatened by climate change. Climate change has emerged as one of the most serious environmental threats that wreak havoc on the agricultural industry [67]. Technologies that can enhance climate adaptation education, including computerised pest-control tools and high-yield seeds to withstand heat and drought, will be necessary to address the problem of climate change [68].

4.4 | Future Direction

The future of these emerging technologies in Sub-Saharan Africa lies in creating a balance between harnessing their benefits and mitigating associated risks. Compared to more developed regions like North America, Europe, and parts of Asia, Sub-Saharan Africa lags in both adoption and regulation. For instance, while South Africa has embraced GMOs extensively, many other countries in the region are still in the early stages of research or policy formulation. In contrast, developed regions have comprehensive regulatory frameworks, advanced research facilities, and public-private partnerships to support safe and efficient technology deployment.

For nanotechnology, countries in Sub-Saharan Africa have only begun exploring applications, whereas regions like Europe and North America are already implementing nanosafety guidelines and conducting advanced toxicology studies. Similarly, while vertical farming is still niche in Africa, countries like Singapore, Japan, and the Netherlands have turned it into a commercial success through automation and policy support. In aquaculture, African nations like Ghana and Kenya are developing their capacities, but these efforts pale in comparison to the intensive aquaculture systems in China or Norway, which are underpinned by cutting-edge technology and stringent safety standards. There is a need for Sub-Sahara African stakeholders to close this gap by strengthening policies and regulations that address biosafety, and nanosafety standards. They should also invest in research and support partnerships to enhance the adaptation of these technologies. There is also a need for capacity building that is, training scientists, regulators, and farmers on the efficient use of these technologies and enhancing public awareness to eliminate misconceptions and build trust among communities. By addressing these areas, Sub-Saharan Africa can leverage lessons from developed regions while tailoring solutions to its unique socioeconomic and environmental context, thereby achieving sustainable food security and technological progress.

5 | Conclusion

Attaining sustainable food security and safety entails a ready source of food both in quantity and quality, for the present inhabitants and future generations. No doubt, the emergence of modern biotechnology such as agrochemicals, GMOs, and vertical farming has greatly enhanced food productivity and allowed agriculture to advance much more rapidly on a trajectory towards sustainability. These new technologies have introduced a new dimension of innovation, providing efficient and cost-effective means of generating a wide variety of novel food for the rising population, and they have a broad and proven track record of improving yield and prosperity in Africa. However, these modern sustainable technologies still face diverse perspectives. Uncertainty about the impact of these technologies on food safety remains a widespread public suspicion. Hence, the safety of the consumed food should be of the greatest importance.

Protecting consumers from unsafe food should be perceived as a commonly shared public policy goal. Ensuring food safety on the continent requires an integrated set of policy approaches. Educating the farmer through food safety education should be intensified while employing modern information and communication technology to provide agricultural extension services. Also, such policies should incorporate regulations, organisations, and multidisciplinary research covering agriculture, social, and health to determine the costs and extent of foodborne diseases fully and to aid in developing cost-effective measures to mitigate or eliminate hazards in food supply chains.

Author Contributions

Deborah C. Chukwugozie: conceptualisation (equal), writing – original draft (equal), writing – review and editing (equal). **Arijeniwa Foluke Victoria:** writing – original draft (equal). **Onawo Genesis Ulakom:** writing – original draft (equal). **Dinah Awino Kawino:** writing – original draft (equal). **Ifeanyi Michael Mazi:** supervision (equal), writing – review and editing (equal). **Helen Onyeaka:** supervision (equal), writing – review and editing (equal).

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Consent

All authors have read and agreed to publish this article.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The authors have nothing to report.

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