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Review Article

Integrating cluster technology and AI in cassava production: A triple helix approach to innovation and sustainability

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ABSTRACT

Cassava is a vital food crop that supports food and economic security in sub-Saharan Africa, Southeast Asia, and Latin America. Its tolerance to poor soils and drought makes it valuable in tropical and subtropical regions. However, cassava production is limited by low yields, post-harvest losses, pests, diseases, climate change, and inefficient value chains. This paper explores the integration of cluster technology and artificial intelligence (AI) within the Triple Helix Model, which promotes collaboration among academia, industry, and government to improve cassava productivity and value-chain efficiency. Cluster technology enhances cooperation among farmers, processors, and researchers through geographic and agro-industrial clustering, reducing costs and improving access to infrastructure and resources. AI complements these efforts through machine learning, remote sensing, real-time disease detection, yield forecasting, and data-driven decision-making. Applications such as drone-based pest monitoring and AI-assisted supply chain management demonstrate the benefits of this synergy. Successful examples include EMBRAPA's AI-cluster programmes in Brazil, which improved cassava breeding, and blockchain-enabled agricultural clusters in Thailand, which enhanced supply chain transparency. Despite these successes, adoption remains constrained by high implementation costs, limited digital literacy, inadequate infrastructure, and weak policy support, particularly in sub-Saharan Africa. The study concludes that integrating cluster technology and AI within the Triple Helix framework can transform cassava production, strengthen food security, improve economic resilience, and support climate adaptation. Stronger partnerships and enabling policies are essential to unlocking cassava's full potential as a strategic crop for sustainable global food systems.

KEYWORDS: *Artificial Intelligence, Food Security, Precision Agriculture, Value Chain Optimization.*

INTRODUCTION

Cassava (*Manihot esculenta*) is a very important food crop, which is widely grown in tropical and subtropical plants and is a major source of dietary carbohydrates to more than 800 million people worldwide (Ayetigbo *et al*., 2018; Alicai *et al*., 2019). It is also quite important in the Latin America, southeast Asia and sub-Saharan Africa, where it is a major earner besides being a diet. Cassava is a source of food insecurity and poverty buffer in these regions especially to the smallholder farmers who solely rely on it as a source of subsistence and financial benefit. Its outstanding ability to adjust in the poor soils, droughts as well as unpredictable climatic patterns highlights its

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importance as a crop that is resistant to climate. In contrast to most other staples, cassava is resistant to environmental stress factors that generally damage the productivity of agricultural activities, and thus, cassava is an essential commodity among rural populations with food insecurity and vulnerable economies (Ayetigbo *et al*., 2018; Bechoff *et al*., 2018).

Other than in food security, the economic benefit of cassava can be seen on its versatility in industry. Some of the value-added products of it include cassava flour, starch, chips, ethanol, and biofuels among others. Some of the items that have been value added include cassava flour, starch, chips, ethanol, and biofuels just to mention a few. These are essential raw materials in industries that produce food, pharmaceuticals, textiles and bioenergy (Bechoff *et al*., 2018). As an example, cassava starch has been used more in the manufacturing of biodegradable plastics, and as a gluten-free substitute in bakery sectors. These industrial applications promise economic diversification and work opportunities especially in the rural economies where cassava farming is the main production activity. Moreover, with the increased value of cassava in international trade, particularly in the exportation of processed food items such as starch and chips, it also increases its significance in the global food system since this cassava provides cheap raw materials to companies throughout the world (Alicai *et al*., 2019).

Nevertheless, although the potential and cultivation of cassava is immense, several challenges have continued to affect the ultimate role of cassava in food security and economic development. In most countries that produce cassava, particularly the sub-Saharan ones, the yield in cassava is much less than the genetic potential of the crop. The reasons that have contributed substantially to this yield gap include low access to better farming technologies, poor management of pests and diseases, low uptake of modern agronomic practices, and insufficient market linkages (An *et al*., 2019). To maximize the potential of cassava as a food security crop in the world, these constraints need to be addressed. Adoption of advanced technological approaches, i.e. improved varieties, climate smart agricultural approaches and new processing approaches could be used to narrow the gap in the products and sustainability.

Cassava is an excellent crop in terms of resilience of food systems and livelihoods in the face of climate change and high population growth coupled with increasing demand in a world where people need sustainable agriculture. Its potential to stabilize food supplies, add to the economic development, and withstand climatic stressors makes it a key to the global efforts to combat hunger, malnutrition, and poverty (Ayetigbo *et al*., 2018; Alicai *et al*., 2019; An *et al*., 2019).

Although it is important across the world, it is important to note that cassava production has a substantial number of challenges, which impede its potential in food security and economic development. These are low yields, post-harvest losses, vulnerability of cassava crops to pests and diseases and climatic change. The current systems of production that are predominantly founded on conventional farming techniques are not capable of mitigating these problems (An *et al*., 2019). Devoid of innovative solutions, cassava farming will remain a victim of inefficiency that restrains it in terms of economic gains particularly in the Global South, where majority of cassava is being cultivated. Its application in the modern times to solve these issues with the help of modern technologies, including artificial intelligence (AI) and cluster technology, has attracted growing interest in recent years (Ayetigbo *et al*., 2018). Nevertheless, the technologies have not been adopted in mass production of cassava, particularly in developing countries because of inadequate infrastructure, absence of technical expertise, and inadequate policy bath. The scattered cassava value chain where farmers, processors, researchers, and policymakers are only loosely coordinated also makes it more difficult to scale up these technologies (Afonso *et al*., 2017). This is a study aimed at exploring how the Triple Helix model, which enhances interdependence amongst the government, business and academia, would be used to integrate cluster technology and AI in cassava production. Through the investigation of the potential of this model, the study seeks to give an insight on how this type of partnership can cause innovation, better productivity and more sustainability in cassava farming. In addition, the study will assess how the technological innovations affect the cassava value chain, focusing on the potential benefits of Global South farmers, processors and the overall agricultural ecosystem.

The promotion of cassava production needs to include the use of artificial intelligence (AI), cluster technologies, and Triple Helix partnership between academia, industry, and government. With the help of geographic clustering and agro-industrial clustering, cluster technology facilitates synergy between farmers, processors, and service providers, as well as efficiency of the value chains, decreases post-harvest losses, and promotes knowledge sharing (Afonso *et al*., 2017; Bechoff *et al*., 2018). AI supplements this by providing new ways of doing things such as predictive analytics, pest and disease detection, and precision agriculture that optimizes the use of inputs, increases yields, and reduces risks associated with the climate (Afonso *et al*., 2017; Bechoff *et al*., 2018). Nonetheless, to achieve the potential of these technologies, Triple Helix collaboration must work correctly the academic institutions do the research and innovation, the industry provides the capital and access to the market, whereas the government should set the enabling conditions and support systems (Afonso *et al*., 2017; Adjebeng-Danquah *et al*., 2020). This interactive methodology will make sure that the technological innovations are viable, scalable, and responsive to the local cassava farming requirements, thus, fostering sustainable development, durability and competitiveness in the cassava industry.

THE TRIPLE HELIX MODEL IN CASSAVA INNOVATION

Artificial Intelligence Research in Cassava Innovation

Artificial Intelligence (AI) is one of the significant contributors in the field of advancing innovation in cassava farming, with machine learning (ML) yield prediction and disease diagnostics being the main applications. The technologies play a critical role in solving major challenges in producing cassava like pests, diseases, and other environmental issues like climate change. The relevance of AI research, in this case, is especially important in the framework of the Triple Helix Model, focusing on the relations of triad cooperation between academia, industry, and government (Arad *et al*., 2020). The collaboration in cassava production has seen the discovery and development of new tools and technologies that are changing the way farming is being carried out, increasing productivity, and making farming activities more sustainable. Among the most evident AI uses in cassava farming, it is possible to name the development of AI machine learning models to identify diseases. Various diseases including cassava brown streak disease (CBSD) and cassava mosaic disease (CMD) may reduce the cassava harvests significantly. Historically, these diseases could be diagnosed by observable symptoms which usually came after the disease had caused extensive harm. However, the recent developments of AIs in image recognition technologies have transformed early detection of diseases. Using computer vision and machine learning algorithms, AI systems can discover disease earlier in its course, often before it is noticeable by the human eye, by examining photos of cassava plants taken by drones or smartphones. The early identification allows a farmer to quickly respond, like administering specific treatments or eliminating the affected plants that would reduce the overall production and the use of the chemical pesticides (Bechoff *et al*., 2018). The second essential field of cassava innovation is yield prediction with the help of AI. To successfully predict crop performance, the yield prediction models apply the information of the past years, environmental, and real-time inputs, such as soil moisture, temperature, and weather. AI-driven processes can analyze large amounts of data to generate insights that help farmers optimize their planting times, input use, and harvesting time. Indicatively, machine learning systems have been developed that can predict cassava harvests, depending on the soil type, and weather patterns, which can help farmers to adjust their practices before the environmental conditions change. Ultimately, the resulting data-driven approach enhances the quality of production predictions, reduces wasting, and ensures the greater efficiency of resources utilization, all of which helps farmers to realize improved financial outcomes (Alicai *et al*., 2019).

Academia, Industry and Government Role in AI Integration

The collaborative nature of the three main stakeholders in the Triple Helix Model, which include academia, industry, and government, is the key to the successful AI research and the potential to apply it to cassava production. The first field that is leading in the field of AI studies is academic research, which is creating novel algorithms and models to detect pests, diagnose diseases, and predict yields (Adjebeng-Danquah *et al*., 2020). In most cases, researchers at universities and research institutions tend to be the major innovators of AI-based solutions, through trials and experimentation, which optimize these solutions to be used in practice in cassava farming. Through their knowledge in computer science, agronomy, and data science, academic researchers are developing the knowledge base that can be used to implement AI tools with great success to the agricultural field. The business sector is important in commercialization and application of these AI technologies. The Agritech companies, startups, and private enterprises work together with academic institutions to transform research into practical tools and solutions that can be applied to the ground. To illustrate, businesses can create AIs-driven software platforms or mobile applications, through which farmers can obtain disease diagnosis services or get their yields forecasts on their smartphones. These solutions developed in the private sector play the critical role of scaling AI solutions and making them available to farmers, in particular, smallholders in rural regions. The industry is also involved in funding and infrastructure in the large-scale implementation of AI technologies in cassava farming.

AI and Cassava Value Chains Synergies

The AI-cassava value chain synergy has become more pronounced with AI technologies tackling the major challenges at different levels of the value chain. AI improved all the facets of cassava farming, including disease control, predicting yield, and making farming more efficient, sustainable, and resilient (Ayaz *et al*., 2019). AI tools can assist farmers to maximize on crop management, minimize loss, and maximize marketable yields as cassava passes through the value chain. Moreover, AI solutions are making the process of managing post-harvesting simpler; machine learning is being applied to find out the most optimal method of converting cassava to value-added products such as chips and flour. With the adoption of AI-based innovations within the cassava value chain, the stakeholders will enjoy more efficiency and high-quality products. Specifically, the cassava processing clusters with the help of AI technologies allow farmers to have improved processing facilities, minimize wastage, and improve the overall value of the crop. Furthermore, AI will help supply chain management teams more effectively, which will enable stakeholders to locate cassava in farm-to-market conditions, meaning the crop is in the best state and at the right time to reach the consumers (Arad *et al*., 2020).

CASSAVA INNOVATION INDUSTRY APPLICATIONS: PROCESSING HUBS AND ARTIFICIAL INTELLIGENCE

Adoption of Cluster- Based Processing Hubs by the private sector

The private sector is the key when it comes to implementation of AI tools and cluster-based processing hubs in cassava production as it serves as a link between innovative research and practical implementation. The idea of cluster-based processing hubs presupposes the communication of multiple stakeholders in a particular geographical region- farmers to processors, marketers, and service providers (Adinsi *et al*., 2019). The hubs provide a collaborative platform, which promotes higher efficiency, low cost of operation, and value chain integration at the benefit of all the concerned stakeholders. The case of cassava has seen the role of the private sector, where they have built these processing hubs and have been the centralized points where cassava is converted to commodities with added value like starch, flour and chips. Availability of these hubs facilitates production as farmers are now able to access convenient processing facilities, which means that they do not have to travel far to deliver their produce to the far-off markets. These hubs are able to bring economies of scale together by sharing cost-saving resources and experience that can reduce the costs of both farmers and processors.

In most instances, such hubs are created with the help of the government with policies that promote the privatization of the agribusiness. The combination of AI technologies into these hubs, which form a cluster, further improves the capabilities of these hubs. The use of AI products, specifically automated sorting and grading machinery, has transformed the process and management of cassava. These technologies ensure that high-quality food is only introduced into the processing chain by sorting cassava roots by their size and quality as well as potential flaws with the help of machine learning algorithms. As an example, AI-powered automated sorting systems can analyze the physical traits of cassava roots, including shape, color, and surface texture and sort them based on them. It does not only enhance the speed and accuracy of processing but also decreases human error and waste that result in the high quality of goods and profitability of the processors (Bechoff *et al*., 2018).

The use of AI tools in processing and value addition

The cassava processing tools that are powered by AI are mainly useful in driving efficiency and maximizing the value that is obtained out of cassava. Besides sorting, AI technologies may also be applied to the processing equipment predictive maintenance, enhancing machine uptime and preventing the occurrence of expensive failures (Ayaz *et al*., 2019). This is because AI systems can predict when a machine is likely to breakdown by analyzing data collected by the sensors installed on processing equipment to enable the maintenance team to conduct preemptive repairs before a significant malfunction takes place. This is an active form of maintenance that helps to minimize downtimes and make sure that processing hubs run at full capacity, which helps to increase the productivity and minimize the cost of operation. The other significant sphere in which an AI tool is creating an impression is the supply chain optimization. As a perishable crop, cassava also needs proper logistics and shipment to be delivered to processing centers still fresh (Arad *et al*., 2020). Using AI systems to optimize the delivery routes can be done by analyzing traffic, weather, and inventory levels to predict the most successful transport routes. There is a waste reduction opportunity through AI solutions that can minimize waste through spoiling by reducing transportation delays and ensuring that cassava arrived at the processing centers at the optimal time allowing efficient processes through machine learning to predict the optimal time and route the cassava could arrive. The quality control designed with AI will guarantee that the cassava products are of an acceptable standard in the industry. AI tools can be applied during the processing stage where real time monitoring occurs, that is, constant checks of variables such as moisture content, starch content and other valuable quality indicators. These systems are able to alert the operators when products go out of the target range and therefore remedial action can be taken. In the production of cassava flour, like, the AI may be employed to determine the consistency and texture of the product, which will be compared against the requirements of the food production company (Adinsi *et al*., 2019).

Incorporation of Academia and Government Partnerships in the Private sector

Partnerships with academia and government that have been built in the Triple Helix Model also allow the use of AI and cluster process processing hubs in the private sector. The role of Academia is that they are the research and development that will produce these AI tools and new technologies (Adjebeng-Danquah *et al*., 2020). Companies also collaborate with research institutions to come up with algorithms that can directly be used in the processing of cassava. As an example, universities can work with agritech firms to customize AI systems to sort and grade cassava, make sure that they are specific to local farming conditions and cassava types. Governments, on their part, promote activities within the private sector by formulating conducive policies that would encourage cassava value chain investment. These policies can be subsidies on adoption of new technologies, tax incentives to businesses investing in agricultural processing hubs and research grants that aim at enhancing processing technologies. The Triple Helix Model allows the scaling of AI-enabled applications in cassava processing by encouraging collaboration between academia, industry, and government, and eventually increase productivity, sustainability, and resilience of the sector (Ayaz *et al*., 2019).

Effects on the Cassava Farmers and their Agricultural Ecosystem

The implementation of AI devices and the processing facilities arranged in the clusters has significant repercussions on the cassava farmers and the greater agricultural ecological setting. To the farmers, having centralized processing systems, which are equipped with AI tools, implies that they will be able to receive more efficient and quality processing services (Adinsi *et al*., 2019). This lowers transportation expenses of transporting produce over long distances, which reduces the post-harvest losses and costs. The use of AI also contributes to better product quality since farmers are in a position of selling their cassava to processing hubs which apply AI to monitor the quality of the product thus guaranteeing more earnings on their product. To the greater farming ecosystem, the integration of AI by the private sector and cluster-based processing facilities leads to the access to the market where cassava is converted to different value-added commodities that can serve both the local and global markets (Bechoff *et al*., 2018). The more that these innovations are spread, the more integrated, efficient, and resilient the cassava value chains would be. This, in its turn, is reinforcing food security by guaranteeing a stable supply of cassava products, which can be used in numerous industries, such as food production or industrial starch applications. The introduction of AI applications and the creation of processing centers based on the clusters is a key step in changing the production of cassava. Using a combination of the Triple Helix model, the private sector, academia, and government can make sure that these innovations are not only viable but scalable to develop a more sustainable, efficient, and competitive cassava value chain (Adjebeng-Danquah *et al*., 2020).

Cluster Technology and AI Synergies

The combination of cluster technology and AI in cassava production offers a tremendous scope of opportunity to enhance production in terms of productivity, sustainability, and efficiency. Cluster technology, including such techniques as K-means clustering, can be used to arrange the production of cassava into more efficient and manageable units, whereas AI technologies can deal with a variety of issues of cassava growing, such as disease detection and yield optimization. These technologies, combined, can revolutionize the cassava production process, making the process more resource-saving, better quality of products, and higher production levels.

Cassava Production Cluster Technology

K-Means Clustering: The K-Means has been applied to create industrial clusters in the production of cassava chips so that targeted development strategies could be applied. An example is that in Regencies Bojonegoro and Malang, they created clusters to enhance the management of raw materials and product innovation (Silalahi *et al*., 2019; Sudirman andTantalu, 2023).

Development Strategies: The clusters will facilitate customized strategies like supplier partnerships, product standardization, and skills training, which are very important to both small and medium businesses in the cassava business (Silalahi *et al*., 2019).

Artificial Intelligence in the Production of Cassava

Disease Detection: To sustain the health and production of crops, AI, in particular, the deep learning models, such as Convolutional Neural Networks (CNNs), are applied to detect the cassava leaf diseases (Tepdang & Ponprasert, 2022).

Price Forecasting: Machine learning algorithms, including Support Vector Machines, have been used to predict cassava prices, which help farmers make informed decisions to make decisions when planting and selling their crop (Fondong& Rey, 2018).

Mechanization and Automation: AI-based mechanization technologies are in development that would solve the issues with cassava production including planting and harvesting that are currently labor-intensive and do not integrate well with agronomy (Li *et al*., 2024).

Precision Agriculture: Precision agriculture is also referred to as smart farming, which involves the application of state-of-the-art technology to enhance sustainable agricultural practices and maximize crop production (Coulibaly, 2024). This method is especially useful in cassava, which is the staple crop to the millions of people in tropical developing countries where smallholder farmers are the predominant group of individuals (Fondong& Rey, 2018; Matshabaphala, 2021). Although cassava is a sturdy crop, intensive farming predisposes pests, nutrient loss, and environmental destruction - issues that can be addressed using smart farming technologies (Coulibaly, 2024).

Smart agriculture is based on the extensive acquisitions of environmental data (temperature, moisture, silk composition) of the environment in sensor networks and allows allocating resources and optimizing yields (Adebola &Ibeke, 2023; Coulibaly, 2024). These networks are complemented by drones with specialized sensors that are able to determine optimum planting time and weed, detect disease and water stress, much earlier than by hand process (Adebola &Ibeke, 2023; Coulibaly, 2024). Plant photos can be interpreted using approaches such as convolutional neural networks, and the obtained data must be analyzed with the help of AI and machine learning, in particular, yield prediction and pest/diseases detection (Mbanjo *et al*., 2021; Adebola and Ibeke, 2023; Ozor *et al*., 2024).

These technologies prove particularly useful in the management of smallholder farms that are clustered or locate in a geographically dispersed manner. Clustering algorithms are used to arrange the groups of farmers and suppliers to gain new knowledge (Matshabala, 2021) and AI-IoT integration provides an opportunity to monitor scattered plots effectively due to remote monitoring (Ozor *et al*., 2024). Combined, sensor networks, drones, and AI will form a potent system of strategic farm management, dealing with the specifics of clustered agricultural activities and enhancing efficiency and productivity in general.

Supply Chain Optimization:

Artificial intelligence (AI) is having a significant influence on supply chain optimization, in particular, better demand forecasting, which can lead to cost-saving and sustainability. AI in Demand Forecasting AI has been an innovative solution to the hard-to-solve issues in the supply chain, such as changing and diverse client demand (Kantasa-Ard *et al*., 2021). The systems based on AI utilize advanced data analytics, machine learning (ML), and deep learning (DL) algorithms, unlike the baseline forecasting processes which are limited by the changing demand and multi-faceted character of the modern supply chains (Kantasa-Ard *et al*., 2021). To help discover patterns and trends, these methods, such as neural networks:

Long Short-Term Memory (LSTM), Support Vector Regression (SVR), and ensemble, will be able to analyze both large volumes of past data and present supply chain inputs (Kantasa-Ard *et al*., 2021; Patil, 2024; Nweje and Taiwo, 2025). Patil (2024) and Nweje and Taiwo (2025) agree that AI models are good at combining several variables, such as external ones, including market trends, consumer trends, seasonality, social media trends, weather conditions, and geopolitics, to offer accurate and consistent forecasts. Services that are especially useful to use AI techniques, including supervised learning algorithms, are the demand forecasting ones. Carrying costs and stockouts have significantly decreased as AI-based forecasting tools have proved to enhance the accuracy of the forecasts (Nweje & Taiwo, 2025).

Clustering and Logistics Costs: The formation of logistics cluster may be of paramount importance to enhance the supply chain efficiency and reduce costs. In the context of a logistics cluster, a higher level of information exchange between the supply chain members is promoted, which subsequently increases the precision of the forecasting and the inventory management (Gruzauskas *et al*., 2019). The result of such coordination of demand and supply due to the joint work of the forecasting models and machine learning algorithms used in the cluster is a decrease in the food waste level and more efficient inventory management (Kantasa-Ard *et al*., 2021). The optimization of AI will be applicable in minimizing the cost of operation through automation of the processes and optimization of the logistical paths, which can be further improved by cooperating in clusters. The cost of fuel and maintenance are reduced by routes optimization, such as the use of real-time data, and delivery is accelerated (Coulibaly, 2024).

Sustainability Benefits: Falatouri *et al*. (2022) and Gruzauskas *et al*. (2019) report that directly, through the logistics cluster, the sharing of information and machine learning helps achieve better demand/supply alignment which directly supports sustainability by maintaining the nutrient levels of products and reducing food waste. Furthermore, research conducted by Patil (2024) and Nweje& Taiwo (2025) found that wastage of unsold goods is decreased because of exact inventory control that is made possible by the precise AI forecasting. Other than cutting down on waste in the distribution process, AI also helps in increasing efficiency of resources in agriculture. Smart agriculture decreases excessive irrigation and avoids waste of water sources, as the irrigation volume and timing are determined through AI-basis sensors and data processing, as well as according to the present circumstances (Coulibaly, 2024). Likewise, the AI models work on data that is provided regarding the nutrient levels of the soil and the requirements of crops to provide particular recommendations on the rates at which fertilizers need to be applied, which will reduce unnecessary fertilizer consumption and negative effects on the environment (Coulibaly, 2024). The examples demonstrate that AI interventions result in resource efficiency. Combined with other AI-based practices in a collaborative model that may be enabled by logistic clusters can enhance these sustainability gains and enable agricultural marketers to minimize waste, decrease emissions, and maximize energy consumption.

CHALLENGES AND BARRIERS

The combination of AI and cluster technology in the Sub-Saharan African cassava production has a high potential of increasing productivity, sustainability, and food security, but the barriers to implementation are significant in three important areas (Ozor *et al*., 2024). On the technological front, the lack of access to quality local data will pose the risk of biased or overfitted AI models, whereas poor digital connection and the lack of computing devices will impede successful deployment in rural areas (Ozor *et al*., 2024; Coulibaly, 2024). Huge technology is another factor that leaves out small scale farmers and disparate systems make it difficult to integrate data across farming platforms (Coulibaly, 2024).

Weak policy frameworks and decades of systemic underinvestment of agricultural research systems institutionally cripple the ability to adopt technology (Mbanjo *et al*., 2021). The lack of coordination of the regional strategies and clear approach to cluster management further complicates such problems, and unsolved intellectual property issues (Ozor *et al*., 2024). Socioeconomic obstacles are also very daunting, with smallholders experiencing prohibitive prices, low levels of digital literacy, most notably rural women and lack of trust of unproven technologies (Matshabaphala, 2021). Farmers are also geographically dispersed and cassava is a perishable crop which makes logistics and processing more challenging.

The successful fight against these interrelated issues needs integrated solutions to the technological constraints that help to reinforce institutional backing and socioeconomic inclusion - key measures to achieve the transformational promise of such innovations in African cassava production and food security (Ozor *et al*., 2024; Matshabaphala, 2021).

CASE STUDIES: TH INITIATIVES, WHICH HAVE WORKED

a) Brazil (AI-Cluster Partnerships of EMBRAPA)

The example of AI-cluster partnerships between EMBRAPA and cassava breeding in Brazil is an illustration of the successful partnership and novel approaches of the organization in agricultural research. EMBRAPA has had a tremendous impact in the agricultural sector of Brazil especially in regions where cassava is a staple crop. The combination of AI and data-driven technologies has made the process of breeding as efficient as possible since it enables the process of selection to be more accurate and efficient. The collaboration between public and private, as well as strategic alliances, has played a crucial role to overcome the financial and administrative challenges, facilitate participatory research designs, and increase global competitiveness of Brazilian agricultural commodities (Cabral, 2021).

The breeding programs of the EMBRAPA have been transformed by new technological developments especially in the fields of molecular biology, genomics, and bioinformatics, which are used to aid in the selection of desired cassava attributes using markers (Amorim *et al*., 2013). The resulting research and development of higher yielding and disease resistant strains of cassava, which are essential to areas that depend on cassava as a food and economic security, have followed (Souza *et al*., 2020). The success of EMBRAPA is an example of a precedent to follow when other breeding projects are being developed, such as banana and soybean breeding, but it is also associated with an issue like the need to constantly innovate and ensure that new threats, such as climate change and pest invasions, are tackled (Cabral, 2021).

b) Thailand (Government-supported clusters + blockchain traceability)

The government-supported clusters and blockchain traceability programs in Thailand have tremendously elevated transparency, efficiency and economic growth in a number of industries. The strategic orientation of the Thai government is specifically its Super Cluster strategy, which started in 2015, is oriented at top-down development to facilitate foreign direct investments (FDI) and increase competitiveness. This plan follows the Asian clusters model that focuses on significant interference and encouragement by the government (Thoppae & Praneetpolgrang, 2021). Also, information and communication technology (ICT) cluster priorities are used to transform Thailand into high-tech industries and enhance technological preparedness and competitiveness on the international level (Surasak *et al*., 2019).

Thailand has adopted blockchain technology to its agricultural and government systems, with a traceability system, using blockchain technology to provide better transparency and integrity of information on agricultural products by real-time IoT traceability. The project has enhanced food safety and supply chain management through a great deal (Charoen, 2012). Moreover, through its e-government efforts, Thai government has been using blockchain, especially in the National Single Window (THAINSW) gateway that facilitates document exchange, enhances governance, promotes transparency, and prevents corruption, which is also found in the overall digital economy vision of the country (Pongnumkul *et al*., 2021). These projects demonstrate the flexibility of blockchain in providing solutions to the problems in the private agrarian sector, as well as the administrative requirements of the state.

LESSONS LEARNT FROM THE SUCCESS STORIES

The success of EMBRAPA's AI-cluster partnerships demonstrates the effective implementation of the Triple Helix (TH) model, where academia (research institutions), industry (private agribusiness), and government (policy/funding support) collaborate to drive innovation in cassava breeding. Several valuable lessons emerge for other regions considering similar approaches. First, EMBRAPA's public-private synergy with universities and agribusinesses, including genomics firms, illustrates how shared resources and expertise can significantly accelerate research and development (Cabral, 2021). This model could be replicated elsewhere through innovation hubs that connect research institutions with local farmers and processors. Second, the crucial role of policy-driven investment is evident in how government backing provided sustained funding for AI and cluster infrastructure (Souza *et al*., 2020), offering an adaptable framework for regions like Sub-Saharan Africa, where public investment in agricultural technology remains limited. Finally, EMBRAPA's technological focus on marker-assisted selection (Amorim *et al*., 2013) and AI-driven phenotyping (Souza *et al*., 2020) provides a scalable blueprint for breeding programs, particularly those aiming to enhance climate resilience in cassava cultivation.

Thailand's integration of government-backed industrial clusters with blockchain traceability exemplifies the Triple Helix (TH) model in action, where government (policy/funding), industry (agribusiness/tech firms), and academia (research/technical expertise) collaborate to drive agricultural innovation. A key success factor is Thailand's Super Cluster Strategy, a top-down approach targeting sectors like ICT and agriculture to attract foreign direct investment (FDI) and enhance competitiveness through significant government intervention (Thoppae & Praneetpolgrang, 2021). This offers a critical lesson for other regions: while strong state leadership accelerates cluster development, it must be balanced with private-sector autonomy to avoid inefficiencies.

In agriculture, blockchain applications have been transformative. For instance, the Jasmine Rice Traceability pilot used IoT sensors and blockchain to track organic rice from farm to export, reducing fraud and buyer rejections (Charoen, 2012). Similarly, in the fish industry, blockchain improved supply chain transparency, addressing illegal fishing and labor abuses while aligning with UN Sustainable Development Goals (SDGs) (Pongnumkul *et al*., 2021). These cases demonstrate that starting with high-value export commodities (e.g., rice, seafood) can prove blockchain's return on investment (ROI) before scaling to other crops.

Thailand has also leveraged blockchain for e-government integration. The National Single Window (THAINSW) gateway streamlined trade documentation using blockchain, reducing corruption and processing delays (Pongnumkul *et al*., 2021). This underscores blockchain's value for bureaucratic processes due to its immutability, though interoperability with legacy systems remains a challenge, a key consideration for other governments adopting similar technologies.

CONCLUSION AND RECOMMENDATIONS

Cassava remains an important crop for food security and rural livelihoods, but its production potential is still not fully realized in many regions. This study shows that combining cluster technology with artificial intelligence, within the framework of the Triple Helix model, can improve productivity and strengthen the cassava value chain. Collaboration among farmers, researchers, private agribusinesses, and government institutions can enhance knowledge sharing, improve access to processing facilities, and promote more efficient production and marketing systems. Experiences from countries such as Brazil and Thailand demonstrate that when supportive partnerships and policies exist, technological innovations can significantly improve cassava production and value addition.

To achieve these benefits, stronger policy support and investment in agricultural innovation are required, particularly in Sub-Saharan Africa. Governments should encourage the development of cassava production and processing clusters that link farmers with processors, markets, and research institutions. Investments in rural digital infrastructure and farmer training are also necessary to enable the effective use of emerging technologies. In addition, universities and research institutes should focus on developing practical AI tools for pest management, yield prediction, and value chain monitoring, while policies should ensure that smallholder farmers benefit from these innovations.

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Authors' Contribution

EBE conceptualized and coordinated the research team, as well as writing the background and the section on "Importance of Cassava as a Global Food Security Crop". NAA drafted the structure of the article and also wrote the section on "Cluster Technology and AI Synergies, AI Synergies in Cassava Production, Challenges and Barriers, Case Studies and lessons learnt". OEU wrote the section on "Challenges in Cassava Production (Yield Gaps, Post-Harvest Losses, Climate Vulnerability)". AO wrote the section on "Role of Cluster Technology (Geographic/Agro-Industrial Clustering) and AI in Addressing Cassava Production Challenges". AAE wrote the section on "Industry Applications in Cassava Innovation: Cluster-Based Processing Hubs and AI Tools".

Ethical Statement

Not applicable.

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