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Review

Automation and control system implementation in a smallholder crop production in Uganda: A review

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Abstract: This review paper explores the potential of automation and control systems in addressing critical challenges faced by agriculture in developing countries, with a specific focus on their applicability in Uganda. The study aims to comprehensively evaluate the role of these systems in enhancing agricultural practices, including the identification of adoption challenges, assessment of potential benefits, investigation of system effectiveness, and provision of evidence-based recommendations. The findings reveal that while there are notable obstacles such as high initial costs, limited technical expertise, and database constraints, there are also substantial opportunities, particularly through the integration of supportive information and communication technology (ICT) strategies and policies. Automation has demonstrated its effectiveness in various agricultural tasks, from mechanized tractors to food processing and livestock farming, offering promising prospects for value addition, irrigation, hydroponics, aquaponics, greenhouse farming, and livestock management. Despite the current modest adoption rates, the study provides compelling evidence supporting the need for increased utilization of automation and control systems in Uganda's agriculture. Collaboration among stakeholders, formulation of supportive policies, development of comprehensive databases, prioritization of tailored ICT infrastructure, and facilitation of knowledge sharing are recommended to overcome challenges and harness the transformative capability of automation. In conclusion, embracing automation holds the key to enhancing the sustainability and food security of Uganda's agriculture, offering valuable insights for policymakers and stakeholders in guiding the sector's future advancement.

Keywords: crop production; technologies; value addition; automation; control systems

1. Introduction

Despite its great contribution to Gross Domestic Product (GDP) and overall livelihood, the agricultural sector in sub-Saharan Africa is at stake due to climate-related challenges. Additionally, there is a fast shift among the population from activities to non-agricultural ventures. This not only reduces the total productivity but also the labor available for production. The adoption of mechanized systems has sought a quick fix for the abandoned venture. However, agricultural production using the current level of technology and the ever-decreasing farm labor availability is likely to make agriculture economically unviable and inefficient [1], hence modern production methods such as automation and control-based systems ought to be adopted [2]. Automation and control systems are widely applied in agricultural production all over the world for optimal utilization of the depreciating resources to meet the requirements of the expanding population considering environmental sustainability. These systems find applications in the crop production value chain during field preparation, irrigation, weed control, harvesting, sorting, grading, storage, and many other operations [3,4]. Automation and control systems involve the use of remote sensing technology, Geographical Information Systems (GIS), Programmable Logic Controllers (PLCs), and agricultural robotics among others [5]. Strategic utilization of control and automation systems holds the potential to enhance agricultural productivity, particularly in developing countries. Surprisingly, there's a lack of knowledge regarding the status of automation and control system implementation within the agricultural sector of sub-Saharan Africa. Nevertheless, understanding this aspect is crucial for recognizing the barriers and opportunities for integrating automation and control systems. Hence, the primary objective of this research is to explore the utilization of automation and control systems across diverse agricultural production value chains in sub-Saharan Africa.

In the past, before the adoption of automation and control systems, agricultural production relied heavily on labor-intensive practices, which predominantly involved manual tasks such as planting, weeding, and harvesting. Irrigation methods were primarily manual, with a focus on techniques like furrow or flood irrigation. Pest control strategies were characterized by limited pesticide usage, often applied uniformly without considering specific needs. Data collection and analysis were minimal, with a heavy reliance on intuition and experience. Additionally, the capacity to optimize crop selection based on data was severely limited (**Table 1**).

Table 1. Past and present status of crop production.

Aspect	**Labor Intensity**		**Irrigation**		**Pest Control**		**Data Collection**		**Crop Selection**	
	Past	**Present**	**Past**	**Present**	**Past**	**Present**	**Past**	**Present**	**Past**	**Present**
Description	High labor requirements	Reduced labor requirements with automation	irrigation	Precision irrigation systems with sensors	Limited pesticide use	Integrated pest management	Minimal data collection	Extensive data collection through sensors, drones, and satellites	Limited data-driven decisions	Data-driven crop selection and rotation
Example of Methods	Manual planting, weeding, and harvesting	Automated planting, weeding, and harvesting	Furrow or flood irrigation	Drip or smart irrigation systems	Uniform pesticide application	Targeted pesticide use based on data	Limited field observations	Remote sensing, IoT devices	Traditional crop choices based on experience	Analyzing historical data for optimal crop choices

With advancements in technology and the subsequent adoption of automation and control systems, there has been a significant reduction in labor requirements, especially in large-scale farms, for tasks such as planting, weeding, and harvesting. Precision irrigation systems equipped with sensors and automation have been implemented to ensure efficient water usage. Integrated pest management practices have evolved, relying on data-driven decisions and the precise application of pesticides. Extensive data collection, facilitated by sensors, drones, and satellites, has become commonplace for in-depth analysis. This shift towards data-driven crop selection and rotation has emerged as a key strategy for optimizing yield and promoting sustainability in agriculture.

In the past, crop production in Uganda relied heavily on traditional farming methods, with limited automation and control systems in place. Farmers predominantly used manual labor and basic hand tools for planting, cultivating, and harvesting crops. Irrigation systems were often rudimentary, relying on manual labor to distribute water to fields. Pest and disease management were primarily based on traditional knowledge and practices, with limited access to modern technologies. In Uganda, efforts to modernize agriculture through automation and control systems have been underway. These initiatives encompass mechanization with the introduction of modern farm machinery like tractors and combine harvesters to reduce labor-intensive farming tasks. Furthermore, irrigation infrastructure improvements, including the adoption of drip irrigation and sprinkler systems, have aimed to ensure a consistent water supply for crops and reduce dependence on rainfall. Precision agriculture practices, utilizing GPS-guided machinery and sensor technology, are gradually gaining ground to optimize planting, fertilization, and pest control.

This table (**Table 2**) provides data on the production rates (in metric tons) for various crops in Uganda during the agricultural years 2014/15 and 2020/21, showcasing the significant increase in crop production attributed to the adoption of automation and control systems in agriculture.

Table 2. Increased crop production due to automation of agriculture.

S/N	Crop	Production rates (MT)	
		2014/15	**2020/21**
1.	Beans	1011	10 million
2.	Maize	2.9 million	10 million
3.	Rice	237,000	680,000
4.	Cotton	17,275	64,750
5.	Cocoa	17,478	25,720
6.	Tea	61,376	112,000
7.	Coffee	211,872	955,890

Source: Ministry of Agriculture, Animal Industry and Fisheries, 2021.

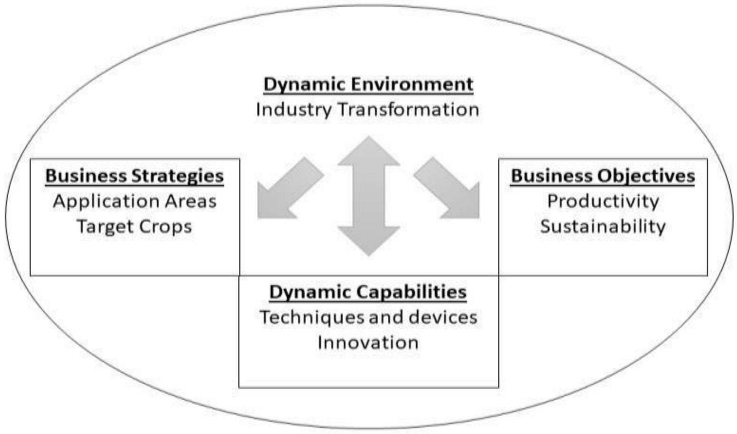

Figure 1. How automation can work to increase crop productivity.

2. Benefits of automation and control system for smallholder crop farmers

2.1. Food security

The population of the world is anticipated to reach 9.7 billion by 2050 and 10.9 billion by 2100, leading to a heightened need for increased food production [6]. In Uganda, the population is forecasted to reach 50 million by 2025, creating a higher demand for food supplies [7]. This population growth places significant pressure on the limited agricultural land resources available [2]. Additionally, the impacts of climate change could potentially harm crop yields [8–11]. To meet the increasing global food demands, there is a requirement for a 70% increase in food production by 2050 [12,13]. To accomplish this target, automation and control systems offer a sustainable solution to enhance food production [14,15].

2.2. Drawbacks of traditional agriculture

The challenges and potential solutions presented in the context of traditional agriculture and the integration of automation and control systems resonate strongly with East Africa, including countries like Uganda, Kenya, Tanzania, and Rwanda [16]. East Africa shares many of the agricultural challenges described, including seed wastage, inefficient pesticide application, soil degradation, and food safety concerns. The adoption of automation and control systems in East African agriculture aligns with the region's efforts to enhance productivity and sustainability [17]. These technologies can help address these challenges by promoting precision farming, reducing resource wastage, and ensuring safer food production practices. As East African nations also grapple with growing populations and the impacts of climate change, automation offers a pathway to boost agricultural efficiency while minimizing environmental degradation [18]. Overall, the integration of automation and control systems in East Africa's agriculture holds the potential to modernize and transform traditional farming practices, fostering economic growth, food security, and environmental preservation in the region.

2.3. Enhance efficiency and productivity

In the context of Uganda's agriculture, the integration of mechanization and automation holds immense potential for enhancing the efficiency and productivity of the country's farming practices. As Uganda faces the challenge of a rapidly growing population, with an expected 50 million people by 2025, there is a pressing need to optimize food production [7]. Automation technologies, including the use of drones, can revolutionize Ugandan agriculture by enabling precise and efficient field operations, such as the targeted application of herbicides and pesticides [19]. Furthermore, automation can bring much-needed precision to various aspects of farming in Uganda, encompassing planting, irrigation, fertilization, pest and weed control, harvesting, and agro-processing, as supported by research conducted by [20–22]. This heightened precision not only reduces resource wastage but also lowers the operational costs of farming, which is particularly important for small-scale farmers in Uganda. By adopting automation and control systems, Uganda can potentially increase agricultural productivity, meet the rising food demand, and achieve sustainability goals in the face of population growth and climate challenges.

2.4. Environmental sustainability

In Uganda, the significance of automation and control systems in agriculture is underscored by the country's specific agricultural landscape and challenges. For instance, in regions like Eastern Uganda, where soil fertility is a concern due to continuous cultivation, precision in fertilization is paramount. Automation systems, as demonstrated by [23] and Lencsés and [24], allow farmers to precisely apply fertilizers, minimizing overuse and soil degradation. Additionally, Uganda's agriculture is sensitive to climate variability, with changing rainfall patterns affecting crop yields. In this context, automation, particularly precision irrigation, becomes invaluable. For example, in the Rwenzori region, where water resources are crucial for banana farming, precise automation systems can optimize water usage, ensuring crop health while conserving this vital resource. Local agricultural experts and institutions like the National Agricultural Research Organization (NARO) in Uganda can affirm the benefits of automation in mitigating environmental challenges and fostering sustainable agriculture. In summary, automation and control systems in Ugandan agriculture not only enhance productivity but also offer tailored solutions to address local environmental concerns, making them vital tools for sustainable farming practices.

3. Application of automation and control systems

3.1. Greenhouse farming

Greenhouse farming has continued to expand in Uganda, with an increasing number of farmers adopting this technology to grow mainly vegetables and flowers. The adoption of greenhouses is driven by factors such as the need for climate-resilient agriculture, improved crop quality, increased yields, and protection of perishable crops from pests and diseases [25]. The controlled environment within greenhouses allows for year-round crop cultivation, mitigating the adverse effects of unpredictable weather patterns and enabling a steady supply of high-demand crops, such as vegetables and flowers [26]. One notable example of the positive impact of greenhouse farming in Uganda is the flourishing floriculture industry. Uganda's greenhouse-grown roses have gained recognition in international markets, contributing to increased export earnings [26]. This demonstrates how greenhouse technology can support the growth of valuable export-oriented crops while maintaining consistent quality and meeting the requirements of premium markets.

Greenhouse farming also aligns with sustainability goals by reducing the need for chemical pesticides and optimizing resource use. As environmental concerns grow, these eco-friendly practices become increasingly important for long-term agricultural viability in Uganda. Furthermore, greenhouses serve as platforms for research and experimentation, essential for developing crop varieties adapted to local conditions and climate resilience. With the rising adoption of greenhouse technology, the integration of automation and control systems is becoming more feasible, promising improved efficiency and reduced labor costs [27]. Automation has been integrated into greenhouse farming to control and monitor the greenhouse environment. The automation system comprises computerized control systems, sensors, and intelligent irrigation systems. The system regulates temperature, humidity, lighting, watering, and other factors that affect plant growth. In some greenhouses, automation systems control the delivery of both water and nutrients through fertigation.

3.2. Hydroponics and aquaponics

Hydroponics involves cultivating plants in water. Combining conventional aquaculture with hydroponics in an integrated system is referred to as aquaponics. The increased hydroponic adoption is linked to highly nutritious, palatable, and digestible fodder for livestock and poultry [28]. Aquaponics technology involves the use of fish waste water for irrigation of crops. The process involves continuous circulation of nutrient-rich water, thus reducing nutrient waste from aquaculture production. Aquaponics has great potential for improving food security and farmers' incomes, especially in urban centers. Balcom [29] notes that aquaponics has the potential to grow crops 10 times more than the conventional system. Also, it reduces the energy requirement for crop production by 75% compared to mechanized agriculture. Aquaponic systems are also considered to be highly water-efficient. According to Okemwa [30], aquaponic systems use 10% or less of the total water used in the conventional system. This makes the technology more user-friendly in Uganda, which has erratic rainfall patterns. That withholding, the performance of aquaponic systems is heavily reliant on the quality of water. Water pH, a critical factor in aquaponics, is quite challenging to balance as plants, fish, and bacteria have different pH requirements. Hence pH must be monitored using precise technologies, and this calls for reliable control systems. Manually operated aquaponic farms such as in Uganda have no potential to achieve optimal pH conditions. Integration of smart control systems that enable real-time monitoring of water pH and water flow is therefore important. The use of sensors such as pH sensors and water pumps helps reduce labor and improve crop yield and water-use efficiency [31].

3.3. Automation and control in agricultural mechanization

Uganda's agricultural sector is a critical component of its economy, employing over 70% of the population [32]. However, it faces challenges such as low productivity, labor shortages, and climate variability. Automation and control technologies hold the capability to address these issues, but their adoption in Ugandan agriculture is still in its infancy. The adoption of automation and control technologies in Ugandan agriculture offers significant opportunities and challenges. Automation can boost efficiency by reducing manual labor and ensuring precision in tasks like planting, irrigation, and harvesting. Modern technologies like GPS-guided tractors and drones can optimize land use, leading to higher crop yields and reduced post-harvest losses. Moreover, automation allows for real-time data collection and analysis, enabling data-driven decision-making for crop management, resource allocation, and market trends. However, several challenges hinder the widespread adoption of automation in Uganda. The high initial costs of acquiring and maintaining automation equipment are often prohibitive for small-scale farmers, who constitute the majority of the agricultural workforce. Additionally, limited access to technology because of the absence of electricity and internet connectivity in rural areas poses a significant barrier. Farmers and technicians also require training to effectively operate and maintain automated machinery, and inadequate infrastructure, including poor road networks and storage facilities, impacts the distribution and marketing of agricultural produce. Furthermore, resistance to change rooted in traditional farming practices and cultural norms can hinder the acceptance of automation technologies. To address these challenges and leverage the opportunities presented by automation, Uganda should consider government support through subsidies, grants, and incentives to encourage smallholder farmers to adopt these technologies. Investment in rural infrastructure, including electricity and internet access, can facilitate the deployment of automation systems. Expanding training programs and extension services to build technical skills is crucial, as is encouraging research institutions to develop automation solutions specific to Ugandan agriculture. Lastly, promoting the benefits of automation and dispelling misconceptions can help shift attitudes towards these technologies. Through these measures, Uganda can harness automation to increase food security, raise farmers' incomes, and promote sustainable agricultural practices.

3.4. Old technologies vs. new technologies

3.4.1. Solar dryer

Existing solar dryer designs, such as cabinet and tunnel dryers, have successfully concentrated heat onto drying items but lack provisions for controlling drying conditions. These dryers, therefore, fail to ensure consistent drying and the attainment of recommended nutritional product quality. Furthermore, these designs rely solely on solar radiation as their energy source, limiting their operation to daytime and rendering them highly susceptible to unpredictable rain and cloudy weather conditions [33]. Another shortcoming of these designs is inefficient heat distribution. Poor heat distribution adversely affects drying quality and capacity [34]. Some products receive excessive heat and become overbaked, while those in colder areas tend to ferment. Consequently, inadequate drying adversely impacts the quality of both nutrition and sensory attributes of the products, diminishing farmers' competitive advantage in securing high-end market prices [35]. Additionally, due to their heavy reliance on solar radiation energy, existing dryers have limited drying capacities per batch, thus hindering widespread adoption by commercial dried food entrepreneurs.

In the realm of high-value crop drying, hybrid solar dryers (HSDs) integrated with sensor-controlled automation systems have emerged as a transformative drying approach in Uganda (**Figure 2**). The HSD uses both solar and biomass heat sources to prolong the drying process even during times of poor solar insolation [34]. These innovative systems, primarily employed in the processing of crops like Arabica coffee, pineapples, cassava, mushrooms, and ginger, introduce a new era of quality preservation and consistency. Central to this transformation is the HSD's ingenious design, constructed primarily from locally sourced materials to facilitate easy maintenance [36]. The pivotal element is the incorporation of semi-automated sensor controls and strategically positioned fans. These sensors vigilantly monitor and adjust crucial drying parameters such as airflow, relative humidity, and temperature.

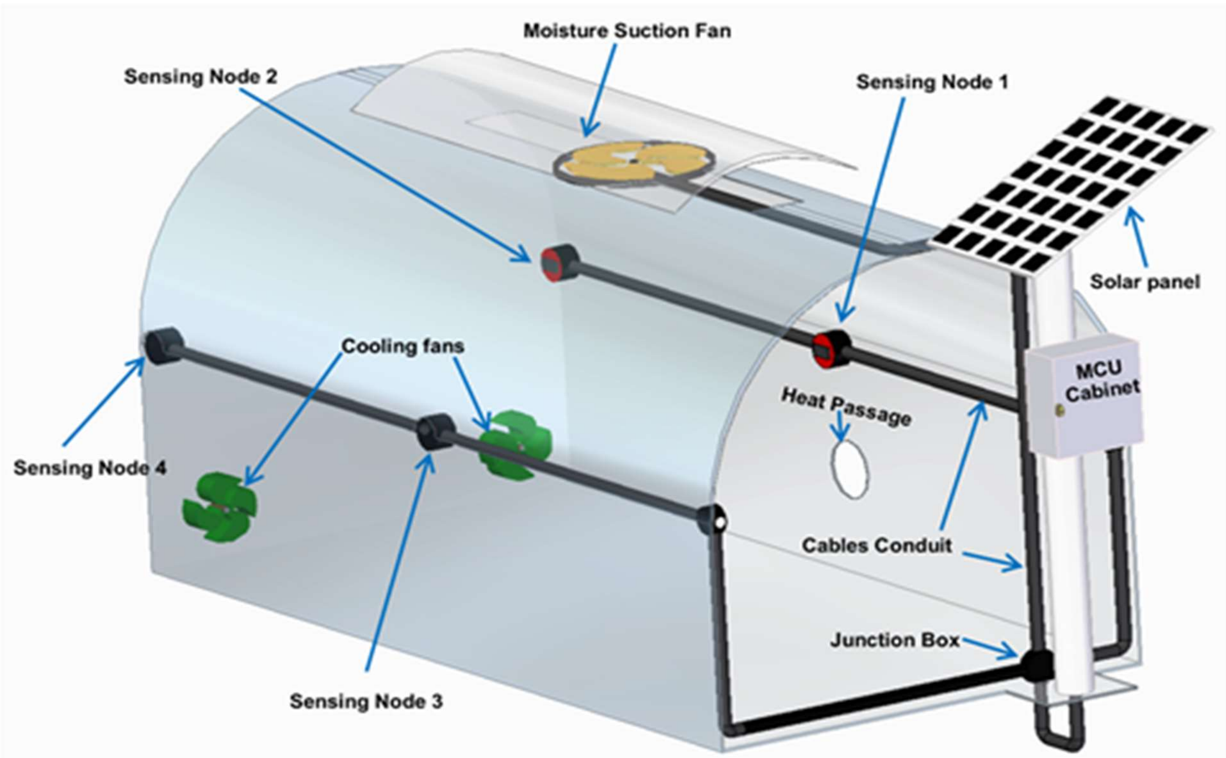

Figure 2. HSD dryer with its constituent parts.

The precise control of drying conditions, specifically temperature and relative humidity as depicted in **Figure 3**, is vital to align them with the specific needs of the crop and the desired quality. This precision ensures uniformity and preserves the nutritional and sensory characteristics of the harvested produce. Additionally, the Hybrid Solar Dryer (HSD) is equipped with a dual-energy source, harnessing both solar radiation and biomass heat energy. This feature guarantees uninterrupted drying, even in adverse weather conditions, effectively reducing the risk of mold formation. Temperature and airflow. The HSD innovation ensures that crucial factors in the drying process are meticulously regulated to prevent damage and ensure consistent results. Combined with a three-stage drying process that adheres to best practices, the HSD ensures the preservation of quality throughout the drying process. Furthermore, the HSD's protective Visqueen covering and multi-layered trays enhance the efficiency of drying, affirming its crucial role in maintaining and improving high-value crop drying operations.

Figure 3. Monitoring relative humidity and temperature of coffee during drying using automatic sensor-based controls.

Namayengo et al. [37] have reported that in East Africa, there is a significant problem of post-harvest loss of fresh perishable fruits, leading to recurring seasonal deficits. In response to this issue, an Improved Solar Dryer (ISD), a cost-effective technology solution for drying fruits in Uganda emerged in the form of an improved passive-mode hybrid solar dryer, as shown in **Figure 4**. This system relies on readily accessible solar energy for the drying process. In contrast, the Solar Photovoltaic and Electricity (SPE) dryer combines both solar photovoltaic and electricity sources for its operation.

Figure 4. The major components of the Solar Photovoltaic and Electric (SPE) dryer [38].

3.4.2. Coffee sorting

Tiwari et al. [39] claim that currently in Uganda, the sorting of coffee and grains is largely reliant on manual labor, resulting in inconsistencies and potential quality issues. A comprehensive machine vision system for sorting coffee and grains currently does not exist in Uganda, highlighting a significant gap in the country's agricultural processing and quality control infrastructure. Implementing a state-of-the-art machine vision system would not only bolster productivity but also ensure uniformity in product quality, thereby improving Uganda's competitiveness in global markets and benefiting local farmers and the economy as a whole [40]. Addressing this gap represents a significant opportunity for technological advancement and economic growth within the country's agricultural industry.

3.4.3. Food processing

Value addition has been strategically adopted to reduce postharvest losses and improve farmer's incomes. Value addition ranges from cleaning, drying, sorting, grading, and thermal processing to packaging. These unit operations are critical for the quality and shelf life of the product [41]. Key attributes to these operations include color, density, size, weight, and skin defects. These attributes are fundamental in bakery, fruit, vegetable farming, and grain production [42]. Therefore, high precision and accuracy are required and cannot be affected using manual methods. Automated unit operations will speed up the sorting, grading, drying, and cleaning to meet the market demand for products at higher prices, including contributing to the global market. Computer vision systems and imaging processing have proven effective for grading fruits, coffee, bread, vegetables, and grains [42,43]. The primary strategic motivation compelling Ugandan companies to invest in Advanced Manufacturing and Processing Technology (AMPT) is that automation systems can be applied to various stages of food processing, such as washing, sorting, cutting, and packaging, followed by a reduction in labor costs. **Table 3** indicates the increasing adoption of AMPT by firms in different food processing sectors in Uganda.

Table 3. Index of automation in production, calendar year, 2017–2021 [6].

Food processing	Year					Annual percentage change-21
	2017	2018	2019	2020	2021	
Meat preparation and processing	68.52	70.54	63.12	42.53	37.70	−11.4
Fish processing and preservation	48.37	57.21	52.96	31.96	25.74	−19.5
Edible oils and fats production	367.63	379.20	453.88	43.26	439.76	1.0
Dairy production	412.63	580.46	730.01	807.67	880.89	0.1
Grain milling	454.82	494.94	493.32	474.17	453.20	−4.4
Sugar processing	196.69	324.11	254.55	276.35	334.99	21.2
Coffee processing	143.27	134.81	148.26	170.80	196.40	15.0
Tea processing	147.95	211.54	178.35	192.20	166.62	15.0
Bakery production	722.29	715.73	858.51	553.39	913.02	65.0

3.5. Meat or milk quality detection

Kunes et al. [45] claim that automation and control instrumentation systems include a range of sensor technologies that can be utilized for assessing meat and milk quality. These sensors can measure parameters such as pH, temperature, fat content, protein content, and bacterial load. They provide real-time data, enabling producers to monitor and maintain product quality [46]. According to Corbett [47]. AI is an expansive field that encompasses various domains, incorporating domains such as machine learning, deep learning, computer vision, and more. It equips us with the ability to scrutinize and make sense of extensive datasets obtained from sensors. Within the context of dairy livestock, AI serves a multitude of purposes. It can discern patterns in livestock behavior and physiological indicators to detect signs of illness, stress, or discomfort. It can also analyze feeding patterns to identify timid eaters and adapt feeding strategies accordingly, as documented by [48]. Furthermore, AI can proficiently recognize and count individual animals in video footage, utilizing data on their feeding behaviors and physiological parameters to enhance feeding schedules and portions.

Automation and control instrumentation systems have made significant strides in enhancing meat and milk quality detection processes in Uganda. In the dairy sector, these systems are widely employed to monitor milk composition, including fat content and protein levels, using advanced spectroscopy techniques [49]. Real-time data from sensors enables precise adjustments in processing, optimizing milk quality, and ensuring compliance with international standards. In meat processing, automation systems are used to monitor critical parameters such as temperature, humidity, and microbial contamination during storage and transportation [50]. This technology ensures meat products are safe for consumption and maintain their quality. Moreover, automation and control instrumentation systems enhance efficiency by reducing human errors and production costs while increasing overall output and competitiveness in the global market [51]. These advancements are instrumental in meeting the growing demand for high-quality meat and milk products, both domestically and for export. IoT-integrated electronic nose system monitors beef odors, tracking Pseudomonas, LAB, bacteria counts, and pH levels in real-time. This data, providing precise insight into freshness and safety, ensures rigorous quality control, allowing swift interventions to maintain high standards in the beef sector, and ensuring consumer confidence and compliance with safety (**Figure 5**).

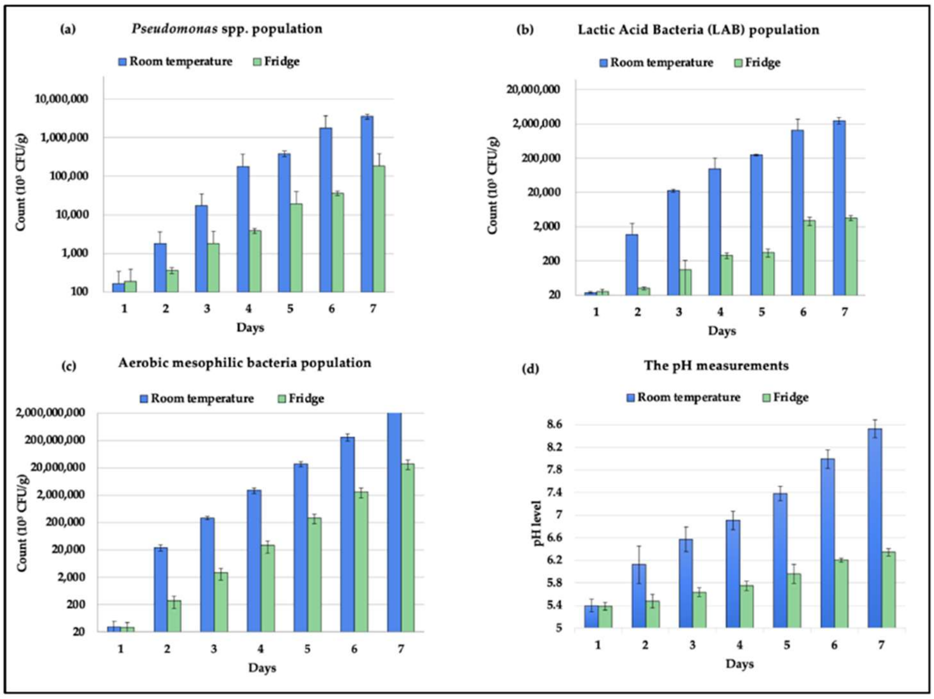

Figure 5. IoT-Enabled Electronic Nose System for Beef Quality Monitoring and Spoilage Detection. The population counts of **(a)** Pseudomonas, **(b)** LAB, **(c)** aerobic mesophilic bacteria, and **(d)** the pH measurements of the beef samples.

4. Challenges

4.1. High skilled labour

Notwithstanding the well-documented benefits of automation and control systems, their use and adoption for agricultural production in Uganda are heavily constrained. To begin with, the initial cost of investment for automated agricultural systems is quite high, especially for small to medium-scale farmers and processors. For instance, a robust drone that can perform multiple farm operations, including routine surveillance, costs as much as $25,000 US dollars [52], a range that is unaffordable by the majority of farmers who would be interested in acquiring it. Additionally, these systems constitute high and recurring operation and maintenance costs. Agricultural credit would be the best alternative to curb the high initial and operation costs. However, there is limited access to affordable credit. The levels of automation always affect the financial status of the farmers. Access to credit enables farmers to procure inputs on time and accelerates the adoption of agro-technologies [52]. However, access to affordable financial services remains a challenge for most smallholder farmers in developing countries [53]. The agricultural sector in sub-Saharan Africa is of a of a majorly small scale, and therefore financing strategies need to be tailored to the smallholder farmers [54]. It is therefore important that agricultural credit is cheap in terms of lending rate and easily accessible to smallholder farmers. Institutions responsible for agricultural credit include banks, micro-finance, and saving and Credit Cooperatives (SACCO). These institutions need to avail the credit at relatively low interest rates to enable farmers to make good on the loans [55].

4.2. Data-driven

Optimal utilization of agricultural automation requires a highly skilled labor force, reliable electric power, internet, and reliable data, among others [56], which is scarce and costly. However, many of the Ugandan industries have adopted the use of automation, but there is still a gap in skills required for the high-end technologies [57]. This is further exacerbated by the limited access to technical personnel. There is little investment in developing a workforce that understands how automated systems operate. According to [58], it is time-consuming to adapt to new technology. This partially accounts for the technical skills of the automation systems. Oftentimes, a breakdown of an automated system, especially in developing countries, requires that the users invite the manufacturers for maintenance and repair. This greatly adds to the cost of operation, making the whole automation system less usable. Taking stock of the local technical capacity-building initiatives, the country has very few institutions offering courses and research relating to automation and controls. A study by [59] in four private universities reports poor funding, lack of permanent academic staff, and poor infrastructure, mainly laboratories, as key challenges. All these challenges are a result of limited funding. Just like private and public universities share challenges of poor funding and infrastructure [49].

In line with operational structures, most if not all automation and control are dependent on machine learning algorithms that are data-driven. The sensors detect and capture real-time data, which is then sent to the data logging center. Many of the automated systems work based on predetermined values. These values can only be managed by developing a database against which the systems make the decisions [60]. According to [61], databases provide insights for future planning during operation. There is no developed database for agriculture in terms of soil types, crop varieties, seed quality, milk quality, and feed quality, among others, in Uganda against which the automation systems can effectively work.

4.3. High cost of internet

Additionally, limited access and the high cost of internet in sub-Saharan Africa add to the operational burden, hence abandonment. Many of the agricultural automation systems are online-based, thus making internet connectivity a key ingredient to automation. However, most of the areas in sub-Saharan Africa have limited access to the internet [62]. The situation is made worse by retrogressive government policies like raising taxes on the internet and blocking some internet sites. Furthermore, internet services are very expensive and inconsistent. The cost of the internet is about 1.50 US$ per GB of data per day. On the other hand, the cost of 1 GB of internet data per day in Kenya, Tanzania, and Rwanda is US$ 0.85, 0.76, and 1.00, respectively. Therefore, sub-Saharan Africa has an expensive internet [63]. In addition to the high internet costs, the unreliability of internet connectivity makes automation even more difficult since it requires a real-time response [64].

Being an electronic-based technology, the function of electricity cannot be downplayed. The majority of the rural areas where much of the agriculture takes place are not connected to the electricity grid. For example, in Uganda, only about 15% of the country is connected to the grid, 7% of which is in the rural setting [65,66]. Even if power is available, it is unreliable. This development has impacted the electric wattage and not the price per unit of power.

Often, machine and equipment design must allow for future modification to cater to changing technological advancements. However, the case is quite different for locally developed technologies in Uganda. The systems are quite rigid, with limited potential for adaptation of high-level automation functionalities. Withstanding, several imported technologies do not suit the local conditions. Nearly all automated technology is imported from Europe, North America, and Asia. Simple laboratory-scale agricultural enabling systems have been developed by a few researchers in Uganda but not actualized for mass production. For example, the Automatic Weather Station (AWS) prototype developed by [67] consists of sensors that automatically gather and transmit weather data to sink nodes connected to a gateway, which then transmits data to the repository. The critical challenge is the limited access to information on automation. Having a clear understanding of the technology helps the potential user to make critical decisions about the type of technology, the capacity, maintenance and repair, and cost-benefit analysis of their farming needs. According to [68], access to information reduces fear and uncertainty about technology and may influence individual decision-making regarding the adoption of the technology.

5. Future opportunities for automation and control systems in crop production in Uganda

Uganda presents several promising opportunities to advance the use of automation and control systems in its agriculture sector. These opportunities are driven by:

5.1. Thriving ICT sector

Uganda's Information and Communication Technology (ICT) sector is rapidly expanding, boasting an impressive annual growth rate of nearly 20%. This growth is fueled by the widespread adoption of mobile services, with over 19.8 million mobile subscribers, constituting 44% of the population. Furthermore, Uganda recorded 27.67 million cellular mobile connections at the beginning of 2022. The increasing prevalence of smartphones, approximately 6 million in recent years, facilitates access to feature-rich digital services and mobile internet policies such as the 2014 National ICT Policy, which is designed to enhance ICT infrastructure and integration across the country and create a conducive policy environment for incorporating automation and control systems into agricultural production.

5.2. Harnessing cutting-edge technologies

Uganda has the potential to leverage advanced technologies such as artificial intelligence (AI), the Internet of Things (IoT), and big data to transform agriculture through precision farming. These innovations align with the global Fourth Industrial Revolution (4IR), characterized by disruptive technologies like AI, blockchain, IoT, big data, drones, and 3D printing. Implementing these intelligent technologies in agriculture can lead to smart and precise farming practices, resulting in increased productivity and sustainability.

5.3. Renewable energy investments

Uganda's growing electrification rate and investments in renewable energy projects present promising prospects for automation systems in agriculture. Private renewable energy companies like Solar Now, Roper Solar, and M-Kopa Solar are addressing the country's energy challenges. Additionally, government initiatives, including the construction of 10 MW solar plants and the commissioning of hydropower stations like Bujagali (250 MW) and Isimba (183.2 MW), are improving energy connectivity, particularly in regions such as Soroti and Tororo. Uganda's abundant solar energy resources, characterized by favorable daily solar isolation, offer the potential to efficiently power automation and control systems, further enhancing agricultural practices. Uganda's flourishing ICT sector, technological advancements, and developments in renewable energy lay the foundation for the integration of automation and control systems in agriculture. As the country grapples with a growing population and agricultural challenges, the strategic use of technology, supportive policies, and renewable energy sources can facilitate the widespread adoption of automation technologies in Ugandan agriculture. This transition holds the promise of improved food security, economic growth, and environmental sustainability for the nation.

6. Conclusion

Whereas adoption is still low, this review justifies the need for automation and control in Uganda. The adoption of automation is envisaged to strengthen value addition, irrigation, hydroponics and aquaponics, greenhouse farming, and livestock production. Automation and control have been observed in mechanized tractors employed in crop management, especially in land preparation, planting, weeding, and chemical application. Automation is observed in food processing with sorting, grading, and drying. Just like crop production, automation in livestock is equally low but slowly picking up in dairy and poultry farming. Most of the livestock farmers continue to use manual systems that are time-consuming, labor-intensive, slow, and inefficient. Little automation is witnessed in cattle and poultry management. Large-scale farmers are effectively using automated milking as opposed to small-scale farmers. The study further notes the challenges and opportunities present for this global technology. The high cost of investment, low automated technologies, lack of technical know-how, limited databases, and lack of guiding policies are some of the hindrances to the technology. Despite that, there is growing opportunity, especially with the supportive ICT strategies, policies, and infrastructure. It would be in the great interest of the different stakeholders, not limited to researchers, government and non-government officials, decision-makers, and other interested parties, to synthesize the findings of this study and make reliable and informed decisions on the future of agriculture in Uganda.

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