Off the Grid: Exploring the design and user agency requirements of AI and IoT solutions aimed at remote, resource-constrained areas in Africa

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Abstract

Rural Africa faces significant challenges in adopting Fourth Industrial Revolution (4IR) technologies due to unreliable infrastructure, high data costs, and limited internet connectivity. This study explores developing and deploying a hybrid hydroponic farming system designed to empower subsistence farmers with agency over connectivity and decision-making. The system integrates solar-powered Internet of Things (IoT) grow tents, a mobile application for real-time monitoring, and a cloud-enabled web platform optimized for hybrid connectivity. Through a farmer-centered co-design approach, we identified the need for flexible connectivity options, local Artificial Intelligence (AI)-driven automation, and remote monitoring capabilities. Our findings demonstrate that farmers value the ability to choose when and how to use data and highlight the importance of agency in technology adoption. The study contributes to sustainable agriculture by demonstrating how AI, IoT, and hybrid connectivity technologies can bridge connectivity gaps, improve resource efficiency, and enhance food security in rural African contexts.

Index Terms—Rural areas, AI, 4IR technology, Hydroponics, Hybrid Technologies

Keywords

Hydroponic farming, Rural areas, Artificial Intelligence, Hybrid technologies, Internet of Things, 4IR technology

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1 Introduction

Like many other continents, Africa is experiencing the effects of climate change, which results in erratic rainfall, increased temperatures, and droughts, increasingly affecting subsistence food creation [7]. This is unfortunate as many rural Africans rely on subsistence farming to ensure they can put food on their tables [49]. Hydroponic farming is thus receiving more and more attention as a possible alternate farming method that can withstand some of the environmental changes mentioned above [31, 54, 57]. This farming method enables farmers to grow crops without needing soil in an environmentally controlled, closed environment [31]. However, hydroponic farming requires constant monitoring, skills, and knowledge [12], which most subsistence farmers have not yet obtained. Many previous authors thus explored the use of Artificial Intelligence (AI) to reduce these barriers to entry [5, 12, 17, 32, 33, 44, 46, 51, 55, 58].

While the proposed hydroponic systems proved effective, they are ill-suited for deployment in remote rural settings such as rural Africa. Africa faces significant challenges in adopting Fourth Industrial Revolution (4IR) technologies for sustainable agriculture [29, 40]. Limited infrastructure disproportionately affects rural areas, including unreliable electricity, high data costs, and inadequate internet connectivity [4]. These barriers hinder the implementation of innovative agricultural solutions, even as the impacts of climate change and the need for resource-efficient practices grow more urgent. Addressing these challenges requires sustainable, context-specific systems [53] that adapt to local constraints and prioritize farmer agency.

This paper extends our previous work in AI and Internet of Things (IoT)-enabled hydroponic management systems. From our previous work, we know that rural subsistence farmers value the ability of these systems to reduce labor, increase plant growth and crop yields, and withstand climate change [Citation omitted for anonymity]. However, although we followed a detailed co-design approach by employing a technology probe, we still made one design mistake: we did not account for farmer agency in data use. Falling into the trap of only looking at the barriers to implementing 4IR technologies, we designed the system only to allow monitoring through a local WiFi network to account for the lack of infrastructure and high data costs. The farmers perceived this design as a lack of agency, explaining that the decision regarding mobile data usage needs to remain squarely in their hands. We thus redesigned our system to empower African farmers with agency over their operations. This is achieved by integrating local and remote connectivity; the system allows farmers to choose between connectivity modes based on their immediate needs and environmental conditions. Developed through a further co-design process, the system features solar-powered IoT-enabled hydroponic tents paired with a mobile application for real-time remote or local monitoring and adjustments, as well as a cloud-enabled web platform optimized for hybrid connectivity [8, 16] access and use. By bridging connectivity gaps, fostering adaptability, and promoting resource-efficient practices, this work contributes to exploring sustainable agriculture technology in Africa. We discuss our background and related literature next.

2 Background and Related Literature

2.1 Climate Change and the Need for Sustainable Agricultural Solutions in Africa

Africa faces severe climate challenges, with rising temperatures, prolonged droughts, and erratic rainfall patterns increasingly threatening agricultural productivity. In rural South Africa, where around four million people are entangled in subsistence farming, climate change is expected to contribute to the already concerning poverty rates [21, 49]. Unfortunately, climate change is also more likely to affect the poor as they lack the means to withstand climate-related challenges [13]. This is especially true for the Eastern Cape and Kwa-Zulu Natal regions, which also house the largest population of subsistence farmers [37].

In Namibia, arid regions like Otjisa in the Kunene region and Donkerbos in Omaheke exemplify the harsh conditions that make traditional farming unsustainable [26]. These areas endure extreme heat, minimal rainfall, and long dry seasons, further exacerbated by limited infrastructure such as electricity and connectivity, and reliable transportation. It is thus not surprising that alternative farming methods, such as hydroponics, are on the rise. Hydroponics, as a water-efficient, soil-less farming technique—offers a promising solution to mitigate these challenges [2] by enabling year-round crop production with minimal water usage. Hydroponic farming, if implemented correctly, also addresses the dual challenge of food security and environmental sustainability in these regions [2].

However, adopting this farming method requires managing nutrient balances, maintaining water pH, and controlling environmental factors. These tasks demand technical expertise, which is often inaccessible to farmers in remote areas [24, 39, 50].

To address these challenges, AI and IoT technologies are recommended to automate and simplify hydroponic management [5, 12, 17, 32, 33, 44, 46, 51, 55, 58]. These systems enable real-time monitoring and adjustments, reducing the need for technical knowledge and making hydroponics more accessible to first-time adopters [citation removed for anonymity]. Such advancements are essential to bridging the gap between sustainable farming methods and practical application in African contexts. However, these systems further need a stable electricity supply and, in most cases, a stable internet connection which can be difficult to achieve given the context and challenges of far-flung rural areas.

2.2 AI and IoT: Barriers to adoption

The digital divide and infrastructural challenges in Sub-Saharan Africa continue to hinder the adoption of Fourth Industrial Revolution (4IR) technologies. While mobile phone penetration has improved—reaching 46% smartphone ownership in 2023, rural areas like Otjisa and Donkerbos in Namibia remain significantly under served [56]. These regions often lack access to reliable service providers, with intermittent or nonexistent network coverage. Namibia further faces stark disparities, where only 51% of the population has access to mobile broadband, and connectivity in remote areas remains below 20% [1]. In South Africa, rural regions experience better network penetration but face prohibitively high data costs, averaging \$2.67 per GB compared to the global average of \$0.50 per GB. [2] For farmers in Donkerbos, the nearest service provider is over 50 kilometers away, and even when available, setup costs for basic connectivity can exceed local monthly incomes. These constraints highlight the need for systems that reduce the dependency on continuous internet connectivity and costly service providers. Hybrid solutions that combine local processing and intermittent cloud access present a practical path forward, ensuring these technologies are accessible and sustainable in remote regions while respecting the agency the farmers have requested. Unfortunately, most existing and proposed AI and IoT-enabled hydroponic grow systems do not take limited connectivity and the crucial role of farmer agency into account.

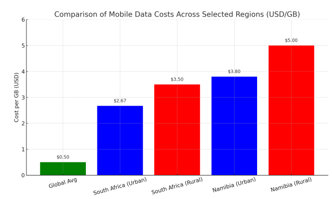

Figure 1: Mobile Data Costs in South Africa, Namibia, and Global Average (USD per GB)

Figure 1 compares mobile data costs between global averages and rural vs. urban contexts in South Africa and Namibia. It highlights the significant cost disparities that rural users face—up to ten times the global average. This visual underscores a key challenge: most AI-IoT hydroponic systems assume affordable, reliable internet, which is not the case in remote African settings like Donkerbos or Otjisa. High rural costs create barriers to accessing cloud-based platforms and services, reinforcing the need for offline or hybrid connectivity models that support localized processing.

2.3 Considerations for agency

Coyle et al. [14] describes agency as the ability to control one's actions and, in turn, affect external changes in the world. The authors further explain that agency is fragile, especially when working with intelligent agents, such as the grow tents, that can make decisions on the user's behalf. The authors further found that systems that can provide assistance significantly impact user agency. For example, user agency declined in their study as the computer-based assistance increased [14]. The grow tents developed in this project were never designed to replace farmers but to serve as a growing companion to assist them in their farming practices. It was thus

[1] https://datareportal.com/reports/digital-2024-namibia
[2] https://www.statista.com/statistics/1274035/price-for-mobile-data-in-south-africa/

important to us that the farmers had agency over the system. This was achieved by providing a mobile application that enabled them to interject should they not agree with the AI's decision (discussed in the methods). Farmers are thus able to make use of a mobile app to manually adjust any setting in the grow tents. This decision was further underpinned by the notion that a critical aspect of sustainable technology adoption is user agency, which allows farmers to decide how and when to use technology based on their unique circumstances [19].

Klingbeil [34] further explains that user agency has transformative potential and fosters freedom in technology use because agency rests on the user's recognition that a manifestation of technology does not necessarily represent the only way the technology ought to be. The authors further state that the inclusion of user agency in technology design challenges the assumptions that technology creation solely relies on expert knowledge and functional properties. In fact, agency refers to the capacity of users to act independently of the technological systems they use and the user's capacity to act upon the design, function, and constraints of these systems to change the conditions of use.

As mentioned before, initial deployments of locally managed hydroponic systems in South Africa and Namibia revealed a strong demand for remote management options, alongside the flexibility to switch to local control when necessary as a further form of agency. This feedback shaped the development of a hybrid model for connectivity, reinforcing the importance of farmer involvement in the design process [22].

2.4 Previous work done on AI and hydroponics do not consider remote or rural areas with poor connectivity

Existing research on AI and IoT in hydroponic farming has predominantly focused on technical efficiency, automation, and optimization, often neglecting the critical aspects of user agency, hybrid infrastructure, and sustainable deployment in low-resource environments. For example, Ramakrishnam Raju et al. [46]'s proposed CNN-enabled hydroponic grow system needs a stable internet connection to send continuous data to Thingspeak [3]. This cloud-based IoT platform requires a stable internet connection to store or retrieve sensor data. Furthermore, Susanto et al. [51] proposes a Naive Bayes classifier paired with sensors that allow farmers to monitor the conditions of the hydroponic system. This system also relies on continuous data payloads sent to Thingspeak; the system further does not account for farmer agency as it does not allow adjustments to the system other than from the AI itself. Pitakphongmetha et al. [43] also recommends using a Naive Bayes classifier but discusses adding remote monitoring via a cloud-based IoT system, which requires internet connectivity. Alipio et al. [3] recommends another Bayesian system, which includes a mobile application enabling real-time monitoring of the hydroponic system through a cloud-based web application; this system also does not consider user agency and requires internet connectivity. Atmaja and Surantha [5], Lakshmi and Hemanth [35] recommends using Fuzzy Logic to grow kale; their fully automated system does not allow farmers to interject or apply agency while using the system. Finally, Yolanda et al. [58] also describes a system that requires a stable internet connection. The fuzzy logic system described in their work also automatically adjusts nutrient and Ph levels, with no plan to include farmers in the decision loop.

Crabtree et al. [15] argue that context-sensitive design is critical for sustainable technology adoption, yet this principle is largely absent in hydroponic AI research. The broader issue with previous research is that it fails to position AI and IoT as tools for empowering farmers rather than replacing their expertise, without a hybrid connectivity design that integrates offline capabilities, local decision-making, and adaptability to varying levels of infrastructure, AI-driven hydroponics risks being another unsustainable intervention that does not fully support agricultural resilience in rural Africa. Addressing these gaps requires a new approach — one that prioritizes hybrid connectivity AI systems, co-design with farmers, and sustainability over pure automation, ensuring that technology enhances, rather than dictates, agricultural practices in low-resource settings.

This research thus examines the re-development and deployment of a hybrid connectivity hydroponics system designed to address these issues. Initially tested in Otjisa and Donkerbos, the system incorporates solar-powered, IoT-enabled hydroponic tents capable of local and remote management. Farmer input was integral to the design process, farmers in both regions expressed a strong preference for remote management. However, they also emphasized the importance of having the agency in choosing when to utilize local versus remote options. A hybrid connectivity system that balances flexibility and autonomy, ensuring farmers can adapt the technology to their specific needs and conditions. We discuss the methodology used to develop this system next.

3 Methods

3.1 Research Setting and Participants

This study was conducted in three locations: KwaZulu-Natal (KZN) in South Africa, Donkerbos in Namibia's Omaheke region, and Otjisa in Namibia's Kunene region. These areas are characterized by high levels of poverty and food insecurity. KwaZulu-Natal further has a large population of subsistence farmers [42], while Donkerbos and Otjisa face significant resource shortages and food insecurity. Given these challenges, these regions provided an opportunity for researchers to engage directly with local farmers, co-deploy hydroponic tents, and investigate potential solutions to food insecurity. Additionally, the study explored the design requirements for Internet of Things (IoT) and Artificial Intelligence (AI) technologies [38] tailored for remote African settings. We discuss each research site individually below:

Sweetwaters - KwaZulu-Natal Province: Sweetwaters is a low-income rural area located 97 km from Durban in the uMgungundlovu district. The average monthly income in this region is approximately R2,400 (USD 1 = R18.51)[4].

To recruit participants in KwaZulu-Natal, we collaborated with the Human Sciences Research Council (HSRC) [5], a governmental research institution with strong connections to local farmers. A

[3]https://thingspeak.mathworks.com/

[4]https://www.statssa.gov.za/publications/P0318/P03182019.pdf

[5]https://hsrc.ac.za/

community liaison assisted in recruiting six farmers, including two community growers who provide food to those in need.

Donkerbos - Omaheke Region: Donkerbos is a San resettlement farm 225 km from Gobabis, Namibia consisting of 470 residents. Participant recruitment followed established protocols from a long-standing collaboration with the community and a local university.

Otjisa - Kunene Region Otjisa is located in the Kunene Region of Namibia , where access to essential resources is limited. The community sources water from nearby streams, and in dire situations, from boreholes in neighboring communities. Otjisa has no access to electricity or internet connectivity, which results in community members traveling to neighboring areas for mobile network coverage, posing challenges to consistent communication.

For detailed demographic information of participants, refer to Table 1. Note that in Donkerbos and Ojitsa, farming is collective, so specific demographic data for individual farmers is not detailed in Table 1[6].

Table 1: Participant Demographic Information, Land Size, and Farming Tenure

Gender	Age	Land Size	Number of Years Farming	Location
F	67	22m x 80m	5	KwaZulu-Natal
F	69	38m x 21m	21	KwaZulu-Natal
F	57	1 Hectare	17	KwaZulu-Natal
F	48	7m x 6m	3	KwaZulu-Natal
M	44	50m x 50m	5	KwaZulu-Natal
Community Collective		174 Hectares	11	Donkerbos, Namibia
Community Collective		n/a	*	Ojitsa, Namibia

*The Ojitsa community is categorized by livestock farming.

3.2 Technology Probes in Co-Design: Engaging Local Communities

This research adopts a co-design approach by collaborating with subsistence farmers to jointly develop and implement hydroponic grow tents in Namibia and rural South Africa. This approach was selected because technologies designed for industrialized nations often fail to succeed in other regions, particularly developing regions, due to cultural and regional differences that end up embedded in technology that subsequently hinder adoption [10]. Many researchers in the Information Communication Technologies and Development (ICTD) space thus advocate for co-design to address these challenges [27, 45]. Ramachandran et al. [45] further highlight the role of social networks and cultural dynamics in shaping technology adoption in developing regions. Later work by Till et al. [53] expanded on this perspective, emphasizing that these cultural and social factors vary not only between countries but also within different regions of the same country. Given these complexities, early involvement of local communities in the research and design process is critical for overcoming barriers to technology adoption [52]. We thus adopt Sanders and Stappers' (2008) definition of co-design as "the creativity of designers and non-designers working together in the design process" [47].

Despite its benefits, co-design presents several challenges. Holeman et al. [27] discuss some of these challenges and complexities in ICTD settings, such as participants' unfamiliarity with new technologies and the power imbalances between researchers and local communities. Cultural nuances also play a crucial role — when acknowledged and integrated into the design process, they can significantly enhance technology adoption and community ownership[53]. However, another challenge, often overlooked in co-design, is the "blank page" problem, where open-ended ideation can overwhelm participants rather than foster creativity [23]. To address these challenges, particularly the unfamiliarity with technology among our communities, we utilized technology probes [30]. These simple, adaptable technologies help researchers understand community needs, facilitate field testing in real-world environments, and prompt discussion about design requirements by enabling participants and researchers to think about technology in new ways [28]. We thus deployed a fully functional IoT and AI-enabled hydroponics tent paired with a mobile application. While we were aware that the deployed probe did not incorporate the specific design needs of the communities involved, we anticipated firsthand engagement with the technology would inspire new ideas and enable participants to contribute meaningful input throughout the co-design process.

3.3 Original design of the hydroponic grow tents

The original design of the hydroponics system uses a black box grow tent designed for controlled indoor cultivation. The tent has a grow light, extractor fan, oscillating fan, 72-hole tiered hydroponic stand, and various peristaltic pumps to deliver a nutrient and pH up and pH down solution to the enclosed water reservoir.

To lower the previously mentioned barriers to entry and simplify the heavy monitoring burden of hydroponic farming for first-time growers, an Arduino Mega 2560 microcontroller installed with TinyML Random Forest Classifier (RFC) classification models housed within a protective water and dustproof electrical box inside the tent is at the system's core. Four different RFC models, each monitoring a different crucial environmental element in the tent: pH, EC (nutrient level), temperature, and humidity, were trained on 5000 records each. The models were evaluated using a Receiver Operator Curve (ROC) as well as an F1 score and Area Under Curve (AUC) . The ROC curve hugged the left corner of the ROC plot, and the AUC and F1 scores were both above 90, which indicates that the model successfully classifies the elements in the tent. The Arduino code was verified through unit tests and edge case tests which are all detailed by the work of Wilson and Mthoko [57].

The four models continuously receive data from sensors that monitor temperature, light, humidity, nutrient levels, and pH in the water. This information is sent to the RFC models, which use an electrical relay box to control various components inside the grow tent, such as fans, lights, and peristaltic pumps. The relay box is fitted with two relays. A 230V relay is used to control the fans, lights, extractor fan, and water pump, whereas the 12V relay powers four peristaltic pumps. The model constantly analyzes sensor data to determine whether the environment inside the tent is within optimal conditions. If it detects any readings that are not optimal, such as the temperature being too high or the pH too low, it sends a signal to activate the appropriate relay to mitigate the sub-optimal conditions in the grow tent

[6]Source: https://www.nau.com.na/farm-donkerbos

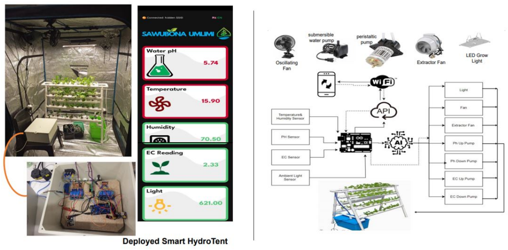

Figure 2: Elements and overall functioning of the grow tents

Finally, the system incorporates an ESP8266-01 WiFi chip, which enables local network communication. This module is responsible for transmitting and receiving requests, allowing manual tent control, and monitoring real-time internal conditions through the mobile application. The application connects to a local network spun up by the WiFi chip, ensuring direct communication between the microcontroller and the user interface without requiring an external internet connection (see figure 2 and 3).

3.4 Original Mobile Application

The mobile application's primary function was to retrieve real-time sensor readings and provide basic control mechanisms for the hydroponic system. Users could view pH levels, temperature, and water flow rates through a minimalist dashboard. The mobile application was initially designed as a control and monitoring interface for the hydroponic system, allowing farmers to adjust water flow, manage lighting and temperature, and view sensor readings. Developed using Kotlin, the app prioritized ease of use and offered the farmers agency, but was limited in functionality as it could only communicate with the system through the local WiFi network. Users thus had to be within a 100m range of the hydroponic setup to access data or make adjustments, which reduced the practicality of the solution, as users had to be close to the system whenever they needed to check readings or make changes. These constraints raised concerns about the long-term sustainability of the approach, as continuous on-site monitoring is neither efficient nor scalable for more extensive operations. There was also no way to access historical data, receive alerts, or adjust any control elements in the tent remotely.

Throughout development, multiple iterations of the application were tested in real-world conditions. The initial offline-only model was found to be too restrictive, as it failed to allow farmers to monitor and control their system beyond the immediate area. This lack of remote access and historical data tracking meant the functional application did not fully support sustainable, long-term agricultural practices.

3.5 Deployment

We deployed six hydroponic grow tents, of which four were deployed in South Africa and two in Namibia. First, we deployed two tents at the offices of a research institute in Sweet Waters, a district within walking distance of the farms of four of the six farmers. The research institute was chosen as a deployment as it had backup generators and stable access to electricity and water. Also, among the six participating farmers, two were members of a quilting workshop that met weekly at the research institute, which made weekly monitoring convenient. These two farmers and the remaining four farmers formed a collaborative group responsible for monitoring and maintaining the deployed tents as community growers. The tent was deployed in October 2023. The additional two tents deployed in South Africa in the Eastern Cape province have not been noted as they were not included in this reiteration of the study.

The first deployment in Namibia took place in Donkerbos, which was considered a favorable deployment site due to the presence of a donated central solar system originally installed to provide access to electricity for the entire community. However, subsequent development in the area has resulted in each house in the community now having a personal solar system. The large, central solar system was thus rarely used. This deployment took place in May 2024. The final deployment took place in Otjisa, which, as mentioned before, had no access to internet connectivity or electricity. We thus sourced and donated a solar system to accompany the hydroponic system. This final deployment was completed in September 2024. The same deployment process, discussed below was duplicated at each site.

The farmers were invited to participate in the deployment process. They worked alongside the researchers to deploy the tents and test their functionality. This process was followed to familiarize the farmers with the system and in an attempt to start building ownership early in the project. Thus, the researchers guided the community in completing the deployment rather than doing it themselves. This involved working with community members to wire the electronics, connect all the sensors, and install the tent, stand, and necessary electronics. Once this phase was completed, we asked the community members to install the mobile application on their phones. The deployment was completed by providing a further hour long training session, which covered the functions of the hydroponic tents, the role of AI in optimizing system performance, as well as features of the mobile application, which were integral to the monitoring process and providing agency.

Following the initial training, informal site visits were conducted where farmers and researchers had the opportunity to interact and reinforce the concepts covered during the training, offering further support and troubleshooting as necessary. These visits were also an invaluable way of reinforcing the concept of agency, as the farmers were empowered with the knowledge to operate the system themselves. During these visits, additional training on hydroponic farming was provided, with a mixed crop of Swiss chard, spinach, and butter lettuce being planted in each tent. The choice of crops was guided by the farmers themselves, who suggested crops commonly grown in the region, thus fostering a sense of ownership and familiarity in the deployment process.

The initial deployments were met with success, as they demonstrated not only the potential of hydroponic systems to provide alternative agricultural solutions in rural areas but also the ability of technology to bridge the gap in agricultural knowledge and resources. This success underscored the critical role of rural communities in the study, showcasing how, with appropriate training and support, even in isolated contexts, technology and sustainable practices can thrive. The mobile application in this scenario was particularly vital, offering real-time monitoring and control for farmers, ultimately highlighting the importance of equipping rural communities with accessible and sustainable technological solutions.

Finally, the research team also installed control tents at the research institutions themselves, providing a baseline for comparison against the deployed grow tents. All six grow tents were successfully functioning and producing crops, marking a pivotal moment in the project's trajectory.

3.6 Data Collection

3.6.1 Observations during site and farm visits. During each site visit, we used the mobile application to check the pH and nutrient solution. Following that, we verified the connectivity and functionality of all components, including the grow lamp, extractor fan, and fan. The plants were checked for pests and fungal infections, and any brown or yellow leaves were removed. These site visits yielded a wealth of useful information about the tents' functionality. If the farmers happened to be present by chance, we would have casual chats with them about their experiences with the hydroponic system and grow tents.

Figure 3: A: A farmer checking the tent during a site visit. B: A healthy crop.

3.6.2 Focus groups. Focus groups were used to enquire about the farmer's perceptions and experiences while using the hydroponic systems. These focus groups took on different forms in different regions. In Kwazulu-Natal, to help the farmers prepare, we sent the questions to be asked at the focus group to the farmers via the WhatsApp group before the meeting. The questions were sent in English and isiZulu. Before the discussions began, the researcher asked for permission for the talks to be recorded. In Namibia, the focus groups were conducted during site visits, as travel to the research sites is costly and time-consuming. The communities in Namibia have long-standing relationships with the research team members based in Namibia; thus, the focus groups took on a friendlier approach.

We further ensured a translator was present to assist with language barriers. The recording was transcribed, and both the recordings and transcriptions were uploaded to a secure data cloud accessible only to the researchers with password access. The recording was then deleted from the recording device.

3.6.3 Whats App conversations. With the consent of the farmers, continuous communication was managed through two WhatsApp groups, one group for the farmers and researchers based in KwaZulu-Natal and another for the farmers and researchers in Namibia. The decision to use two WhatsApp groups was based on the fact that the farmers were from different countries in Africa and they did not have the same challenges and climates. We had open and candid conversations about sharing mobile numbers on WhatsApp groups. We carefully made sure the farmers and researchers felt comfortable with the arrangement before proceeding. Finally, to ensure that the farmers themselves incurred no costs, we provided mobile data to the farmers.

3.7 Data Analysis

The research notes, WhatsApp chats, and focus group transcriptions were analyzed thematically using Braun and Clarke's approach of inductive thematic analysis [9] to establish the common and uncommon themes that arose. The researchers then generated themes that spoke to the experiences of deploying hydroponic grow tents and coded them accordingly. To ensure agreement on the themes, the researchers reviewed and discussed the themes alongside the farmers. The final refined themes are presented in our findings.

3.8 Limitations and Ethical Considerations

Ethical clearance was obtained in July 2023 (Ref. No. 3971). All data were stored securely on an institutional cloud with two-factor authentication. Written notes were digitized and destroyed. Verbal consent was obtained prior to all participant interactions, with translation support provided in participants' preferred local languages.

Given the high cost of the hydroponic system (ZAR 13,000), equipment was donated to participants. No farmers incurred expenses, and efforts continue to reduce system costs and improve contextual suitability. Deployed tents will remain with the communities post-study, with ongoing technical support. Procurement considered local supply chains, and all design materials are open-source to support broader adoption and re-usability.

4 Findings

In this section, we first discuss the feedback we received from farmers with regard to remote monitoring and pest control, which prompted the system enhancements, which we discuss next with a particular focus on how we adapted the system to 1) update the hardware to enable the agency to meet the farmers' requests. 2) Redesign the mobile application to make the agency visible to the farmers, and finally, 3) updates made to the system to account for the farmers' contexts and environments in the hope of designing a more scalable and sustainable solution.

4.1 Farmer Feedback: Agency in remote monitoring

The farmers shared their experiences while using the grow tents and thus provided several recommendations and adjustments to the system going forward. One such recommendation was that the grow tent be connected to the internet so that they could access and monitor the tents remotely. When asked about the cost of mobile data the farmers indicated that they were willing to spend money on data where it matters. One of the Kwazulu-Natal-based farmers offered the following explanation:

"I would like to check the tent from home because it is not easy to come to Sweet Waters all the time due to transportation."

The farmers repeatedly asked for remote monitoring to be implemented with one farmer mentioning:

"I want to decide when to use my data or not. It may be cheaper to use data than to travel to the tent some days. The decision should be ours when we want to spend money or not."

The remote nature of the deployments, particularly in Otjisa and Donkerbos, made this capability even more vital. In Donkerbos, the community leader took responsibility for managing the grow tent but faced logistical challenges due to the village's isolation. The nearest central town is over 200 kilometers away, and transport — when available — is prohibitively expensive (approximately NAD 700 or USD 37.49). This meant that the leader was often away for extended periods, during which he could not monitor the tent or respond to system faults. Although the grow tents are semi-automated, they still require human oversight to ensure consistent performance.

Otjisa presented additional infrastructural challenges, with no access to electricity or the internet. These conditions further emphasized the need for hybrid connectivity — systems that can operate both offline and online. While Otjisa could not currently support remote monitoring, the community expressed a strong desire for such functionality should stable internet become available in the future.

4.2 Farmer Feedback: The need for local and remote pest control and monitoring

The farmers in South Africa further faced many issues with pest control. The hot and humid climate in KwaZulu-Natal creates ideal conditions for aphid and spider-mite infestations, potentially destroying the tent's crops. Aphid infestations happen quickly and are very hard to manage. Early detection and treatment is crucial. The farmers mentioned the following:

"In tent 2, I found Aphids and Cutworms. - They eat the leaves and decrease crop quality"

The farmers then requested a pest control system and mentioned:

"That could help me a lot because it can reduce manual labour, enhance early detection, increase accuracy and support data-driven decision making. Such systems would make crop management and pest control easy."

We would also find aphid and other pest infestations when checking on the grow tents during site visits. This resulted in the development of an offline Convolutional Neural Network (CNN) model responsible for the reporting and handling of pest infestations. We discuss this and further enhancements made to the system next.

4.3 System Enhancements: Enabling Agency through remote monitoring

4.3.1 Hardware enhancements for easy and stable local and remote connectivity. The original ESP8266-01 module was replaced with a NodeMCU ESP-12F, which ensures more stable communication and enables dual-mode connectivity (local and remote). The upgraded ESP12F module and app now recognize WiFi Service Set Identifier (SSID) and display network information, aiding in visualizing whether the farmers are using local or remote control. This ensures farmers can manage their tents with or without internet access, using only their phones and the tent's local network, reducing reliance on costly mobile data while still preserving the farmers' request for agency . Figure 6 illustrates this feature.

We next refactored the Arduino code to allow HTTP requests via the internet or intranet, depending on the farmer's needs and decisions. This upgrade ensures functionality is retained even when internet access is unavailable. Further refinements were made to improve system functionality and address the dependency on the ESP8266-01 module. Initially, system functionality relied entirely on this module, meaning that if the ESP8266-01 failed, the system would still function. However, all monitoring, local or remote, would fail. To mitigate this issue, the code was refactored to separate concerns, ensuring that the system remains operational even without a local network connection.

Remote access also extends to visual monitoring; an ESP32-CAM module, installed in the grow tent, provides live video streaming over the internet. Farmers can now inspect the physical state of plants, check for stress or disease, and stay informed about environmental changes without needing to be on-site.

4.3.2 Enabling remote pest control. This camera feed also works hand-in-hand with a custom-developed AI-powered pest detection system. Images captured by the ESP32-CAM are sent to a custom-developed CNN model to support the farmers with pest detection, using a Raspberry Pi for local model inference and the ESP32 camera for live image capturing, operating entirely off-grid via local WiFi without relying on internet connectivity. The model was trained using a custom CNN architecture, transfer learning with VGG16, and a publicly available dataset focused on the most common pests, such as spider-mites and aphids. Deploying the CNN model on the Raspberry Pi proved the feasibility of automating pest detection in resource-constrained settings. However, this model is currently only deployed in the campus based control tents to ensure its proper functioning before deploying it with the farmers. Continuous monitoring is essential, especially because pest infestations can escalate rapidly. One challenge we encountered was visibility at night or in low light. To address this, the system includes a remote flashlight toggle that turns on an internal LED in the camera, enabling night-time inspection inside the tent. The system currently notifies the farmers if pests are detected. However, the current configuration can be easily adapted to make use of the existing 12V relay system to mist with the necessary organic pesticides also to provide mitigation. Together, these upgrades ensure that the grow tent system remains adaptive, intelligent, and responsive — supporting sustainable farming practices even in resource-constrained or remote environments.

4.4 Making Agency Visible - Mobile Application Enhancements

The mobile application was updated to be an integral component of the hydroponic system, leveraging a hybrid IoT network to enhance agency and accessibility. Farmers can now interject, should the AI make a mistake, from any location they may find themselves in.

However, the local connectivity and features remain, ensuring that the system is operational even in areas with poor internet connectivity. This was also achieved by replacing the ESP8266-01 WiFi module with the NodeMCU ESP12F, enabling seamless connectivity and WiFi SSID Recognition. The WiFi recognition is important as it enables farmers to connect to the correct network to enable remote or local monitoring and adjustments. To achieve this, the application retrieves the device's IP address and connected network name (SSID) using location and internet permissions, improving network transparency by visually indicating which network the farmers are connected to (see figure 5). However, the local connectivity and features remain to ensure that farmers can choose how and when to access the internet to manage their tents. To achieve the above, several key user interface (UI) and performance improvements were thus introduced:

- **Offline/Online mode indicator** The system now clearly indicates if the farmers are using the application in offline or online mode.
- **Multilingual Support:** The application now supports all 11 official South African languages, promoting inclusivity and ease of use across diverse communities.
- **Tent Identification:** Each grow tent is easily identifiable through the SSID, displayed prominently in the top-left corner of the interface.
- **Live Camera Integration:** Real-time visual monitoring of the tent environment is enabled through an ESP32-CAM module.

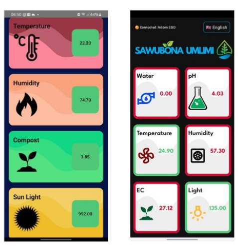

Figure 4: Comparison of the old and new mobile application.

Figure 6 illustrates the evolution of the mobile interface, contrasting the original version of the application with its current, feature-rich design. Finally, the use of edge computing by leveraging local AI processing on the Arduino Mega2560 ensures real-time responsiveness even in low-connectivity regions.

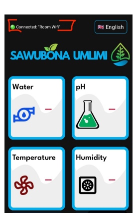

Figure 5: Application SSID retrieved.

4.4.1 Custom Push Notifications for Sustainable Decision-Making. To increase agency and proactive farming alongside the tents, the system now implements custom push notifications that alert farmers when critical environmental parameters fall outside optimal ranges. These real-time alerts help prevent crop failure and reduce wasteful energy or resource consumption. The following triggers would result in a push notification sent to farmers' mobile phones should the AI not automatically rectify the issue:

Low Light Levels: Alerts farmers when lux levels drop below optimal, allowing them to adjust grow lights for efficient photosynthesis.

Humidity Deviations: Notifies farmers when humidity levels are too high or too low, prompting adjustments to prevent plant stress.

Temperature Fluctuations: Prevents extreme heat stress or cold exposure by alerting users to take necessary actions.

pH Imbalances: Ensures optimal nutrient absorption by warning farmers of pH instability, preventing soil acidification or alkalization.

Nutrient Level Anomalies: Triggers alerts when nutrient levels are too low, ensuring the nutrient solution is balanced for sustained plant health.

These notifications function in both remote and local modes, allowing farmers to still get updates if they are within range of the tent and, therefore, do not want to use mobile data, as well as remotely, enabling them to make decisions and adjustments when they are away from home.

4.5 Honoring the farmer's context

4.5.1 Removing the dependency on an installed mobile application: Web-Based Administration and IoT Integration. While most African farmers own a Smartphone, these devices usually are older and, in our case, have failed, leaving a farmer without a device to monitor and control the tent. To mitigate reliance on a mobile phone, the option of connecting to the tent via a web-based application was also provided. This web-based application also allows for local and remote monitoring.

The NodeMCU ESP12F further assisted in extending the system's capabilities beyond the mobile application by functioning as a dedicated web server. This web-based platform operates in two distinct modes: online and offline. In online mode, it connects to the Internet, allowing users to send HTTPS requests remotely, which enables full control over the grow tent from anywhere in the world without the need for the installed mobile application. In offline mode, the NodeMCU spins up a local web server, enabling access to the web app without an active internet connection. This ensures that users in rural or remote areas can still monitor and control their system within a local WiFi network, eliminating the dependency on cloud services.

The web-based dashboard further acts as an admin panel that provides real-time sensor data visualization and manual control over critical components within the grow tent. Users can thus still monitor key environmental parameters such as nutrient and pH levels, humidity, temperature, light intensity, and water pump activity. The web app further also allows for precise adjustments to ensure optimal growing conditions for crops. Additionally, the system offers a manual control interface, enabling users to toggle grow lights, fans, water pumps, and other IoT-connected devices in real-time. HTTP-based protocols facilitate communication between the interface and the hardware, ensuring low latency and efficient command execution.

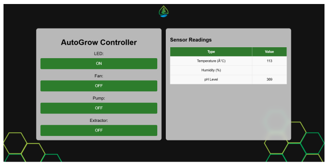

Figure 6: Spun up NodeMCU ESP12-F Server (Online/Offline).

4.5.2 Exploring Solar-Powered Hydroponic Systems as a Solution to Africa's Energy Challenges. South Africa faces severe energy challenges, including frequent load shedding, grid instability, and high electricity costs, disproportionately affecting rural communities. Many regions, particularly Donkerbos (Botswana–Namibia border region) and Otjisa (Namibia), have limited or no access to reliable power, making conventional farming difficult. To ensure food security and agricultural resilience in these areas, alternative energy solutions are essential.

To address these issues, we designed and tested a solar-powered hydroponic system capable of functioning independently of the national grid. Our system incorporates an EcoFlow Delta Max 2 solar chargeable backup battery, chosen for its high battery capacity, portability, and ability to sustain critical hydroponic components such as water pumps, LED grow lights and environmental monitoring sensors. We successfully developed a working prototype through extensive testing and refinement. This system is currently undergoing further field testing and co-design iterations in Otjisa. The deployment in Donkerbos is successfully running on the already existing solar system. This community has also worked alongside the researchers to redevelop the design of the grow tents into an entirely different system, more consistent with their needs. This system is currently deployed in Donkerbos; however, we are still actively collecting data and will thus include the details of this system in later work (see Figure 7

Figure 7: The solar-powered deployed tents in Donkerbos

4.6 Sustainability and long-term viability through community engagement

Beyond functionality, our focus was on creating a sustainable system that can operate efficiently in the long term. This requires integrating energy-efficient components, ensuring local accessibility to maintenance resources, and developing training programs for farmers to manage and troubleshoot the system independently. We thus provided each farmer with thorough documentation detailing how each component in the tent functions as well as the steps needed to repair the electronics in the tent should they fail. We have already borne the fruits of this process with the community leader in Donkerbos actively repairing breakages in the tent, without the need to contact the researchers for assistance.

Developing this solution has been a lengthy and iterative process, requiring multiple site visits, continuous adjustments, and overcoming repeated failures. Harsh environmental conditions, including fluctuating sunlight availability, dust accumulation, and water supply limitations, have required constant refinements. However, community involvement has been central to our progress — working closely with local farmers has helped us tailor the system to real-world needs, ensuring that it remains practical and impactful.

5 Discussion

5.1 Design for Agency

From our findings, it is clear that a key consideration in the design of AI and IoT hydroponic systems aimed at rural farmers is user agency, ensuring that farmers and community members retain control over decision-making while benefiting from AI-driven insights. While we initially did consider agency in our original design, omitting the agency in data usage was an unfortunate oversight. In our case, the farmers displayed agency as defined by Klingbeil [34] as the user's capacity to act upon the design, function, and constraints of technological systems to change their conditions of use. Our farmers repeatedly requested the agency to change not only the conditions in the tent but also how and where monitoring the conditions was possible. A slight lack of agency regarding the connectivity of the tents resulted in the farmers speaking out and asking for their agency back. Consistent with previous research, we observed that increased technology-based assistance led to a decline in user agency [14]. We further concur with Coyle et al. [14] that agency can be particularly fragile when systems provide decision-making assistance. However, an interesting addition to these findings is that users will start defending their agency if they know it is possible. This can be seen when the farmers in our study felt that their agency was under threat when a decision regarding the connectivity of the tents to the internet did not include their voices. They were used to having a sense of control, knowing that they could take over and address any element in the grow tents should the AI not act as it was supposed to. Not having agency in how the system connects to the internet resulted in the farmers stating that how and when they use their data should be their decision entirely.

Our findings further suggest that the future of AI-powered hydroponics in Africa should focus on context-aware solutions — systems that blend automation with farmer expertise. Rather than imposing rigid automation that might seem disconnected from local practices and realities, the system should be designed to adapt to the farmer's knowledge, experience, and needs [48]. Such adaptive systems provide more tailored solutions and drive sustainable agricultural innovation. When farmers can seamlessly integrate their traditional knowledge with the capabilities of advanced technologies, they are more likely to adopt and continue using these solutions in the long term.

Finally, our findings reinforce the idea that user agency is a critical factor in sustainable technology adoption, as it enables farmers and community members to determine how and when to use the technology based on their unique circumstances [19]. In the case of the farmers in this study, we strongly concur with [34], who states: "Agency, in short, rests not on a particular consciousness; it rests on glimpsing possibility." One of these possibilities was the design of a hybrid system that meets their needs.

However, in designing for agency, it is equally important to recognize the broader socio-environmental constraints that shape user engagement in rural settings. Beyond the cost of internet access, farmers in our study many of whom were older adults faced additional barriers such as long travel distances, lack of reliable transportation, and physical limitations. Visiting the grow tents often involved journeys of several kilometres, sometimes on foot or through expensive public transport. These challenges impacted their ability to respond promptly to environmental changes or technical failures. Designing for rural contexts must therefore go beyond digital accessibility and consider infrastructural realities, mobility constraints, and ageing demographics. By reducing the need for physical presence through robust remote monitoring, and ensuring that systems remain intuitive and low-maintenance, we can better support agency in practice not just in principle.

5.2 Design for Flexibility: Hybrid Connectivity, Low Electricity Consumption, and Solar Capabilities

Our findings also indicate that current system designs and recommendations related to AI and IoT-enabled hydroponic grow systems are ill-suited to rural African areas, as these systems do not account for the lack of electricity, connectivity, or mobile data costs in these areas. Furthermore, the importance of precision agriculture in hydroponics underscores the need for hybrid systems. [20] explains that hydroponics requires precise control over nutrient delivery, pest management, and environmental factors to ensure optimal plant growth. Our findings show that local data processing enabled by deploying hybrid AI-IoT systems utilizing offline AI models significantly enhances real-time decision-making, even in areas with no internet connectivity. Thus, the use of offline TinyML models that are capable of functioning without internet access and on little electricity has proven to be useful in remote areas. However, the option to make use of internet connectivity, when available should always remain an easily accessible option. This integration can significantly enhance operability across sub-Saharan regions [7] by enabling dynamic adjustments in nutrient dosing, pest control, and other environmental factors without continuous internet connectivity. The hybrid model becomes exceptionally crucial in this case as cloud-based solutions, while powerful, can be highly dependent on continuous internet access, making them unreliable in regions where connectivity is intermittent or unavailable [36]. A system that processes data locally ensures that the AI in the tent can function alongside the farmers, who can continue to monitor and adjust critical variables such as nutrient levels, pest control, and environmental conditions, even when the internet is inaccessible. The same is true for pest control, the use of an offline model means that the functionality to automate pest control can exist, even in areas where there is no electricity supply and no connectivity. Thus, by reducing reliance on constant online access, hybrid systems create more resilient, autonomous solutions capable of operating in areas with unreliable or limited internet connectivity. This flexibility is crucial for African agricultural settings, where internet infrastructure can be inconsistent and local challenges such as power shortages and extreme climate conditions further complicate agricultural management [2]. The concept of braided technology [18] supports this perspective, arguing that technology adoption is most effective when it interweaves with established workflows rather than imposing rigid automation. The farmers in this study have a long history of toggling the mobile data on their phones on and off. They require systems that enable the same freedom. Finally, the hybrid approach to AI-powered hydroponics could also play a pivotal role in overcoming some of the key barriers to technology adoption in African agriculture, such as a lack of trust in automation or resistance to change. By providing a system that operates effectively with or without the Internet, farmers are more likely to experience immediate benefits, which can increase their willingness to embrace further innovations. This approach ensures that the long-term impact is sustainable, helping subsistence farmers adapt to changing conditions and thrive in a rapidly evolving agricultural landscape [26].

5.3 Why should we care

Brewer et al. [10] and Ramachandran et al. [45] have long been advocating for contextually relevant solutions to meet the needs of developing regions. In our work, we have aimed to do just that. To work alongside the farmers in an attempt to co-create a system that acts in a way that is acceptable and suitable to their communities. However, one could argue that these systems are expensive and that low-resource subsistence farmers are unlikely to afford the necessary equipment outside this study. However, in African agriculture, where many rural farming communities face challenges such as unreliable internet connectivity [56] in addition to the difficulties their wealthier counterparts are experiencing with climate change, solutions to their problems almost become more important. It is crucial not to underplay the role of subsistence farmers in poverty reduction and food security [49]. This becomes especially evident when one considers that over 4 million South Africans are in some way entangled with subsistence farming [6]. Subsistence farmers further assist with informal employment and income generation [49]. The World Economic Forum further estimates that approximately 70% of Africans rely on the food produced by small-holder farmers [7]. We thus argue that one should investigate the use of new and expensive technology for developing nations, especially in areas as critical as food production [53]. Brewer et al.[11] explain that technology can be considered one of the greatest enablers of life, and not looking at how to enable these communities could be costly in the long run.

[7] https://www.weforum.org/stories/2024/04/heres-how-we-protect-smallholder-farmers-and-food-security/

One should also consider the fact that being expensive today does not equate to being expensive tomorrow. Emerging technology cannot be disregarded on its current feasibility alone, as a technology futures analysis may indicate that continued research and adoption of the technology would lead to a decrease in the cost-benefit [25]. This is evident in the exponential mobile phone diffusion rates in South Africa [1], where researchers once had to consider the use of mobile applications on smartphones carefully; the country now has more mobile connections than people, with most South Africans owning a smartphone. We, therefore, agree with Okolo [41], who advocates for AI development that prioritizes the needs of marginalized communities and elevates their status not just as beneficiaries of AI systems but as primary stakeholders. Therefore, we must not exclude the voices of those who also stand to benefit from AI and other cutting-edge and possibly expensive technologies, but rather include them as stakeholders in a responsible and ethical manner.

6 Recommendations and Future Work

The initial nutrient dosing mechanism is crude and does not consider the amount of nutrient solution currently in the water before dosing. Instead, the system doses a preset 1 milliliter of nutrient solution. Should the readings be suboptimal? Future work should focus on refining the precision of nutrient delivery. The initial pest control system will also require future refinement and enhancement. Furthermore, leveraging environmental data for early-stage pest detection offers significant potential. By analyzing humidity, temperature, and image data, the system can initiate automated responses, such as lighting or ventilation adjustments, or push notifications to alert farmers. This proactive strategy reduces dependency on manual inspections or chemical pesticides, promoting more sustainable farming practices.

In addition, predictive models that utilize the same Raspberry Pi-based infrastructure as used for the current pest control system are currently under development. These predictive models will monitor crop growth and identify early signs of stress or disease through computer vision. These models will also allow the system to intervene autonomously or prompt the user to do so, helping to maintain high-quality yields with minimal manual input. As such, future iterations focus on expanding the machine learning component to include plant health forecasting and dynamic decision-support systems.

Another important area for future work is the analysis and optimization of bandwidth consumption. While the current implementation transmits real-time environmental data and camera feeds, we did not formally measure data usage. Future deployments should thus include bandwidth monitoring tools to assess the volume and frequency of data transmission across both local and remote modes.

Furthermore, we could explore lightweight communication protocols, data compression, or scheduled transmission intervals (e.g., syncing only during specific times of day) to reduce data strain. These optimizations would conserve bandwidth and lower the costs associated with mobile data, making the system more accessible to rural communities.

Finally, given its modular design, the system has the potential to be adapted for other forms of controlled-environment agriculture or educational use. We are currently exploring the AI system for fodder production in rural Namibia. The system can further work without any of the original components, meaning that farmers can use a shade cloth structure that negates the need for the grow lights and fan, or a tunnel that would negate the need for the light but include fans, etc. This is possible because the AI-driven core logic is not dependent on specific hardware, allowing for substitution with local equivalents. The open-source GitHub-hosted codebase[8] enables replication and expansion, making the system a viable foundation for other digital agriculture initiatives in both high- and low-resource contexts.

7 Conclusion

AI and IoT-enabled hydroponic systems are often recommended to deal with the effects of climate change. Unfortunately, the design of the majority of these systems does not account for the contextual differences and infrastructure challenges present in rural African regions nor do they consider including farmer agency in their design. We advocate for the design of a contextually situated AI and IoT-enabled hydroponic system that includes farmer agency and considers the unique challenges mentioned above. We found that building a hybrid system that makes use of TinyML offline models paired with hybrid connectivity may address many of these challenges. We further advocate for a design that focuses on farmer agency, especially when including intelligent agents in agricultural solutions. Finally, we argue that the cost of technology should not deter from work aiming to discover the unique design requirements of low-income small-scale farmers who put food on millions of tables.

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