The Devil is in the deployment: Lessons learned while deploying an AI and IoT-enabled hydroponics grow tent with rural subsistence farmers in South Africa

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ABSTRACT

Hydroponic farming is a sustainable alternative to traditional agriculture, allowing farmers to grow crops more efficiently. This type of farming involves growing plants in water without needing soil. There is increasing agreement that this agricultural approach should be utilized to mitigate food insecurity, particularly considering the fluctuating and unpredictability of weather conditions. However, this approach requires technical expertise in addition to consistent monitoring. Existing research has focused on applying The Internet of Things (IoT) and Artificial Intelligence (AI) technologies to the automation and monitoring of hydroponic farming systems. However, limited work tested the viability of these systems in the field with farmers. This study focused on including rural subsistence farmers in farming alongside a seven-month and ongoing deployment of an AI and IoT-enabled hydroponics system following a qualitative approach that entailed focus groups with the farmers and observations of the hydroponic systems. This paper discusses the lessons learned regarding unpredictable and uncontrollable extreme weather conditions, equipment failure, choices in nutrient solutions, and pest infestations, which often all have unplanned and unintended consequences for these systems and farmers. We argue that more deployments are needed to better understand how these systems function in real-world settings.

CCS CONCEPTS

• **Applied computing** → **Agriculture**; • **Computing methodologies** → **Planning for deterministic actions**; **Artificial intelligence**.

KEYWORDS

Hydroponic farming, Artificial Intelligence, Internet of Things, Deployment Lessons Learned

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1 INTRODUCTION

Subsistence farmers form a large population of South Africa and play an imperative role in the economy. Subsistence farming allows for the provision of nutrition and plays a role in decreasing rural poverty. [53]. Lately, South Africa has faced drastic and unpredictable environmental changes. This has left many farmers with increased temperatures and rainfall, which have destroyed farmland and crops[41]. Hydroponic farming, which grows crops in a controlled environment, often without soil, is suggested as a possible mitigation and alternative method to address these challenges [30]. However, hydroponic farming requires skill, knowledge, and constant monitoring [11]. Previous studies [4–6, 11, 15, 21, 31, 33, 34, 44, 45, 48, 55–57, 62, 63] have therefore explored the use of Artificial Intelligence (AI) in the form of Machine Learning (ML) models and the Internet of Things (IoT) to automate and monitor hydroponic systems. However, to our knowledge, the envisioned systems are rarely deployed with farmers. We designed, six AI and IoT-enabled hydroponic grow tents capable of growing a variety of leafy green vegetables, in particular we planted spinach and butter lettuce. The tents were deployed with five farmers in KwaZulu-Natal, and two farmers in the Eastern Cape regions of South Africa [30]. We closely monitored the farmers experiences and interacted with the farmers throughout the growing process through WhatsApp, face-to-face focus groups, and interviews.

We found that while the system was able to grow crops at an accelerated rate, reduce labor, and circumvent climate conditions such as erratic rainfall and expected shifts in temperature, there were many lessons to be learned from this deployment. This paper discusses lessons regarding unpredictable and uncontrollable extreme weather conditions, equipment failure, infrastructure choices, and pest infestations, while shedding light on how future deployments could evolve and shape farmers co-growing experience with technology.

2 BACKGROUND AND RELATED WORK

2.1 The impact of climate change on subsistence farming in South Africa

There is a global agreement that the escalating climate change poses a significant threat to humanity [19] because it increases temperature trends and unpredictable rainfall patterns [16]. In South Africa, climate change is expected to increase food insecurity and poverty levels among rural people who depend on subsistence farming [19]. It is, therefore, important to note that subsistence farmers account for over four million of the South African population. These farmers grow crops for their own family's consumption and to reduce food insecurity [2] [3] [54] as surplus produce is sold informally[2]. Subsistence agriculture is crucial for ensuring rural people's livelihood and food security. Unfortunately, climate change directly impacts the poor because they cannot withstand climate-related challenges [12]. The communities in the Eastern Cape and KwaZulu-Natal regions predominantly experience poverty in South Africa. This has increased the number of rural subsistence farmers forced to grow crops to feed their families. Unfortunately, climate change has adversely affected their efforts due to extreme weather conditions, namely droughts, increased temperatures, and storms, which cause soil erosion and the inability to cultivate the land, resulting in massive crop losses [36]. It is thus not surprising that alternative farming methods, such as hydroponics, are on the rise.

2.2 Hydroponic farming

Hydroponic farming can be classified into six methods: 1) Ebb and flow, which relies on the flow of nutrient-rich water over the roots of plants for a fixed duration of time. 2) Deep water culture (DWC), where plant roots are submerged in nutrient-rich water aerated by an air pump. 3) Wick systems use a cotton or nylon string submerged in a water reservoir, providing water to plants often planted in soil or other solid growth mediums. 4) Drip systems that continuously provide plants with water and nutrients. 5) Aeroponics involves using water mist to provide nutrients to the roots of plants often planted in vertical hydroponic stands, and finally, 6) Nutrient Film Technique, which continuously flows nutrient-rich water over the plants' roots. NFT is the most prominent method of hydroponic farming and relatively easy to implement [17].

Hydroponic farming often produces bigger yields when compared to plants grown in soil [18], uses 13 times less water, and, when practiced in grow tents, can eliminate the dependence on the natural climate.[35]. This farming method is thus a viable option for a water-scarce country like South Africa, particularly in rural areas with poor water service. However, the technical skill requirements and regular attention to manually monitor, measure, and adjust the environmental and nutrient requirements of the plants [1, 27] may prove daunting to first-time hydroponic farmers [1]. Many researchers are therefore using AI to monitor and automate some of the tasks in hydroponic farming, reducing the knowledge requirements and management overheads [48].

2.3 Previous work and Recommendations for AI and or IoT-enabled hydroponic systems

Many different AI algorithms and systems have been recommended to automate hydroponic systems. Ramakrishnam Raju et al. [48] describe an IoT and Convolutional Neural Network (CNN) implementation that uses IoT to monitor output from the soil, sunlight, humidity, pH, and temperature sensors. The CNN monitors the leaves of the plants to determine the optimal nutrient levels and to prevent pests. Susanto et al. [57] describe a system that implements a Naive Bayes classifier and sensors that will allow farmers to monitor the conditions of the hydroponic system. Pitakphongmetha et al. [44] recommends using a Naive Bayes classifier but discusses adding remote monitoring via a cloud-based IoT system. Alipio et al. [4] further added to the work done on Bayesian systems by including a mobile application that enabled real-time monitoring of the hydroponic system. Kaewwiset and Yooyativong [31] tested implementing a Linear Regression (LR) model to adjust a hydroponics system's EC and pH levels automatically. Atmaja and Surantha [5], Lakshmi and Hemanth [34] describes the use of a multi-step fuzzy logic system used to grow and monitor kale whileVelazquez-Gonzalez et al. [62] propose a system that uses Fuzzy logic to calculate the correct pH dosages for hydroponic systems.Yolanda et al. [63]expanded on fuzzy logic implementations by automatically adjusting the EC and pH levels of the nutrient solution of an NFT hydroponics system. In line with the works above, the majority of the studies implementing fuzzy logic focused on monitoring and controlling pH and, or EC in NFT hydroponic systems through the use of sensors [6, 15, 21, 55], control the water pump in an Ebb and flow system [11], the water pump, foggers and dehumidifiers of an NFT system [33] and only the pH in an Ebb and flow system [56]. Finally, the NFT FL system tested by Puno et al. [45] monitored and controlled pH, water drainage, EC, temperature, and humidity. To our knowledge, none of the work cited above tested the viability of these systems in the field with farmers.

3 METHODS

3.1 Research Setting and participants

This research took place in KwaZulu-Natal (KZN) and the Eastern Cape (EC) provinces of South Africa. High poverty and food insecurity levels often characterize these provinces. [1] Both provinces also house the highest concentrations of subsistence farmers in South Africa, presenting us with an opportunity to work closely with subsistence farmers while co-deploying hydroponic tents and exploring ways for addressing food insecurity [37]. However, this paper reports on the deployment in KwaZulu-Natal.

Sweetwaters - KwaZulu-Natal Province: Sweetwaters is a low-income rural area located 97 km outside Durban, South Africa in the uMgungundlovu district. This area has an average household

[1] https://www.parliament.gov.za/storage/app/media/Pages/2020/october/06-10 2020_sectoral_parliament_planning_session/day1_session1/ A_Poverty_Mapping _Overview_of_the_Poorest_Provinces_Metros_Districs_and_Localities_in_SA.pdf

income of R2,400 per month 4 (USD1 = R18.71) and [2] comprises around six hundred thousand people. The district is representative of the Zulu population in KwaZulu-Natal, with 100% of the population listed as isiZulu speakers [3].

To recruit participants, we partnered with the Human Sciences Research Council (HSRC) in KwaZulu-Natal [4], who have been actively involved and working closely with farmers in the province. The community liaison thus recruited five farmers, two of which were community growers who provides food to community members in need free of cost.The demographic information of our participants is detailed in Table 1.

Gender	Age	Farming Land Size	Number of Years Farming
F	67	22m x 80m	5
F	69	38m x 21m	21
F	57	1 Hectare	17
F	48	7m x 6m	3
M	44	50m x 50m	5

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

3.2 Co-Design approach with technology probes

This work takes on a co-design approach working alongside subsistence farmers to co-deploy and explore hydroponic grow tents in rural South Africa. Technology designed for industrialized nations often performs poorly in developing nations [10] because these nations often have cultural and regional differences, which can have detrimental effects on the adoption of technology. Brewer et al [10] therefore advocated for a Co-Design approach when working in the Information Communication, Technologies and Development (ICTD) space. Ramachandran et al. [47] also discuss challenges such as social network structures and cultural information. These cultural differences and norms also often reach further than just between industrial and developing nations but can present within the different cultural and geographical areas of a single country [60]. It is therefore important to include communities in research processes as early as possible to better understand and account for these sociocultural contexts[61]. We, therefore, refer to Sanders and Stappers (2008) [51] who define co-design as "The creativity of designers and people not trained in design, working together in the design process" as our approach for this research. However, Holeman et al. [25] highlight some of the difficulties of co-design in ICTD settings, from the alienness of the materials typically used to increased power differentials between the researcher-designers and the end user-designers. Being cognizant of these challenges, particularly the alienness of new materials, and because we were asking participants to co-design alongside us, using technologies they had never encountered, we also considered the blank page problem [29], which occurs when no limitations or expectations are placed on creativity. This is often called the paradox of choice, where too much freedom in creative choice can be overwhelming [29]. Garfield [22] states that a lack of boundaries does not necessarily liberate creative processes but enslaves them. Many researchers and participants have experienced this problem while working with new technologies or ideas in a co-design setting. Moreover, we noted from past experience working in the area that our farmers have experienced ideation fatigue resulting from a "blank page" approach. So, after careful consideration, we decided to use technology probes. Technology probes are simple, flexible, adaptable technologies that 1) help researchers understand the needs and desires of their participants, 2) allow researchers to field test technologies in a real-world setting, and 3) enable users to think about new technologies [26]. We thus built and deployed a fully functional IoT and AI-enabled hydroponics tent and accompanying mobile application to allow our participants time to experience the technologies to elicit easier and more meaningful conversations about the community's design requirements. We were thus fully aware that the system, in its initial form, did not consider the design requirements and needs of the community but would instead serve as a probe to start conversations and hopefully enable participants and researchers to think about and articulate the system's design requirements, and share their experiences.

3.3 System Design and Implementation

To mitigate the erratic weather patterns currently present in South Africa [5], we decided to implement a fully enclosed hydroponic system, which included temperature, light, and humidity control. We, therefore, used a dark box hydroponic grow Tent [6] with 80cm x 80cm x 160cm dimensions, which contains a 72-hole step-down tiered hydroponic food grade PVC grow stand [7]. The humidity and temperature in the tent are controlled with an oscillating multi fan [8] and a mixed-flow inline extractor fan [9]. For the necessary lighting and heat we made use of a full spectrum LED grow light [10]. The necessary nutrients are supplied via an eight-liter water reservoir fitted with a submersible water pump [11] capable of pumping water 1.2 meters to reach the top tier of the growing stand. The system is gravity-fed from here with an outlet pipe draining into the water reservoir to complete the water circuit.

3.3.1 IoT network and mobile application application. To enable the farmers to visualize and help monitor and maintain the controlled environment, we installed a DHT22 temperature and humidity sensor [12], an ambient light sensor [13]as well as pH [14] and Electrical Conductivity (EC) sensors[15]. These sensors transmitted real-time

[2]https://www.statssa.gov.za/publications/P0318/P03182019.pdf
[3]https://wazimap.co.za/profiles/municipality-KZN225-the-msunduzi/
[4]https://hsrc.ac.za/
[5]https://www.weathersa.co.za/Documents/Corporate/WeatherSmart%20Newsletter%202023%20v5%20(1)_06112023131312.pdf
[6]https://www.takealot.com/dark-box-hydroponic-grow-tent-80cm-x-80cm-x-160cm/PLID69343156
[7]https://www.bellandpaton.co.za/products/hydroponic-step-down-tiered-growing-system-72-holes
[8]https://gthydro.co.za/products/1339-ram-180mm-7-oscillating-multi-fan-eu-plug.html
[9]https://gthydro.co.za/products/1465-ram-mixed-flow-inline-fan-100mm-4.html
[10]https://plantliving.co.za/products/samsung-lm301b-full-spectrum-led-grow-light-110w
[11]https://www.takealot.com/sobo-submersible-water-pump-15w-880-l-h-max-height-1-2m/PLID90152378
[12]https://www.dfrobot.com/product-1102.html
[13]https://www.dfrobot.com/product-1004.html
[14]https://www.dfrobot.com/product-1025.html
[15]https://www.dfrobot.com/product-1123.html

Parameter	Sample	Optimal Range
EC	0 – 4.5	1.8. - 2.5
Humidity	60 – 80	65 -75
pH	4.0 – 7.0	5.8 - 6.3
Temperature	15 – 28	18.3 – 25.0

Table 2: Sample and Optimal values in synthetic dataset

Parameter	Classification	Equipment	Turn to State
Temperature	Low	Light	On
Temperature	High	Light	Off
Temperature	Optimal	Light	Off
Humidity	Low	Extractor fan	Off
Humidity	High	Extractor fan	On
Humidity	Optimal	Extractor fan	Off
pH	Low	pH up pump	On
pH	High	pH down pump	On
pH	Optimal	pH up pump	Off
pH	Optimal	pH down pump	Off
EC	Low	Nutrients pump	On
EC	High	Water pump	On
EC	Optimal	Nutrients pump	Off
EC	Optimal	Water and Nutrient pumps	Off

Table 3: Parameter Status and AI Action

sensor data to an Arduino Mega 2650 RV3 AT micro-controller[16]. We next created a REST Application Programming Interface (REST API), which served JSON data over a local WiFi network using an ESP82066-01 WiFi module[17]. This WiFi network, paired with an Android-based mobile application, enabled the farmers to visualize the sensor data in real-time. The application further allowed farmers to adjust settings through API requests should the Machine Learning (ML) model make any mistakes. This application was developed through several co-design iterations where the farmers would report on the challenges they faced while using the application.

3.3.2 Machine Learning model and system automation features. We used the Random Forest Classifier (RFC) to train models to automate the system by classifying whether the parameters in the grow tent were in an optimal or sub-optimal state. The RFC can predict one parameter; therefore, four models were built for each of the temperature, humidity, EC, and pH parameters. Real-time sensor data was fed into the models at 5-minute intervals for temperature and humidity and every 16 hours for pH and nutrient (EC) levels. The AI would next classify the state of the tent and adjust any element (temperature, humidity, nutrient level, pH level, or light readings) of the tent by turning on or off the necessary element or by using small (100 mils per minute) peristaltic pumps to either pump nutrient or pH solution in or out of the water reservoir.

3.3.3 The use of and need for synthetic data. Unfortunately, we found few publicly available hydroponic datasets to train the models for the EC, pH, temperature, and humidity parameters. We, therefore, decided to make use of synthetic data. The use of synthetic data is familiar to ML with Hittmeir et al. [24] reporting on empirical experiments that found that synthetic data had little to no adverse effects on the accuracy of ML models. These findings were echoed by Jordon et al. [28]. We thus used the random module of the Numpy Python library to generate the datasets. For each parameter, a sample range that included the optimal range and levels considered too high or too low was identified, as shown in Table 1. Random numbers in the sample range were then generated, and each was labeled as low, optimum, and high, which are the three class labels needed for the AI action, discussed in the next section.

This process gave us a dataset for each parameter of at least five thousand records used to train the RFC models. The validity of the dataset was achieved by looking at the F1 score of above 70% , the classification report for the model as well as the AUC (Area Under Curve) and ROC (Receiver Operator Curve) which were all in the acceptable ranges with the AUC curve hugging the left corner of the AUC plot. We further validated the data with a successful crop growth in the control tent on campus before deploying the system with the farmers.

3.3.4 Model training, evaluation, and deployment. Finally, we used the datasets to train the needed RFC models with the default parameters of the sci-kit learn Random Forest Classifier library. X and y datasets representing independent and dependent variables required by the RFC were created from the synthetic datasets. These were further split into training and testing sets in the ratio 80:20, enabling the models to be evaluated using separate data from that used for training. The trained models were evaluated using accuracy scores and confusion matrices.

We finally deployed the ML models to the Arduino Micro-controller by porting the Python model to C++ using the micromlgen Python package, [50]. The models predicted the class labels based on sensor data, and the AI took action accordingly, as specified in Table 2.

The reliability and validity of the Arduino program were achieved through unit testing and boundary value testing [13]. The parameter values at the class boundaries were used to check if the program classified correctly on the transition between low to optimum status and between high and optimum and if the AI took the correct action.

3.3.5 Considerations for failing electricity infrastructure in South Africa. South Africa faces the worst rolling blackouts in the country's history [20]. These rolling blackouts, locally called load-shedding, are planned electricity outages implemented in different stages. The blackouts can last from two hours in stage one to six continuous daily hours in stage eight. It was, therefore, crucially important that the grow tents could withstand up to 48 hours without electricity. The hydroponic stand inside the grow tents drains slowly using only gravity to drain the water. This process takes time and enables the plants to survive up to 48 hours until all the nutrient-rich water is drained from the hydroponic stand.

3.4 Deployment

We created six grow tents, four deployed with rural subsistence farmers. Two tents were deployed on the farms of two farmers in Gqeberha. While a total of five farmers from KwaZulu-Natal

[16]https://store.arduino.cc/products/arduino-mega-2560-rev3
[17]https://www.sparkfun.com/products/17146

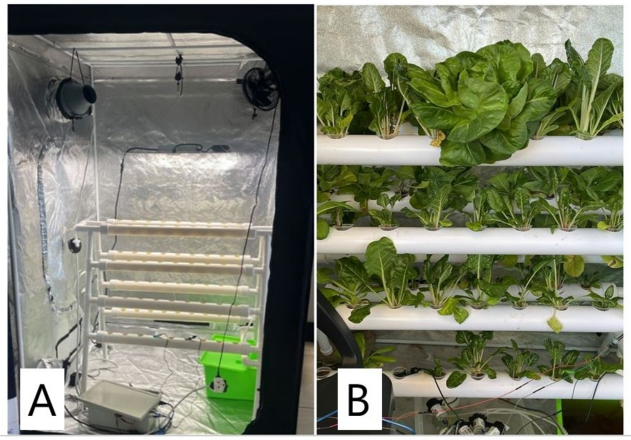

Figure 1: A: A fully constructed AI and IoT enabled grow tent. B: example of crop growth

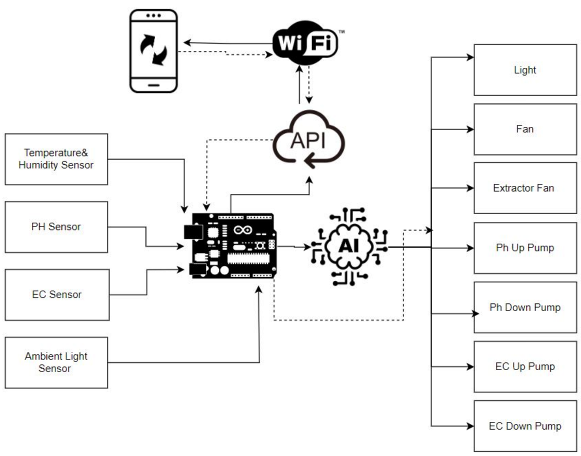

Figure 2: AI and IoT automation system present in each tent

joined the study. We, therefore, installed two tents at the offices of a South African research institute in the Sweet Waters, within walking distance of four of the five farmers. Two of the KwaZulu-Natal-based farmers belong to a quilting workshop that meets once a week at the research institute's offices. The Kwazulu-Natal-based farmers formed a group that monitored and maintained the tents. The remaining two grow tents formed the control tents at the researcher's institutions. All four tents were deployed in October 2023. The farmers were invited to participate in the deployment, after which we asked them to install the mobile application on their phones. We finally provided an hour-long training session that focused on the functions of the tent, the role of the AI, and the features available in the mobile application. This information was reiterated during informal site visits when the farmers and researchers met by chance when checking on the tents. We further provided training on hydroponic farming and finally planted a mixed crop of Swiss chard spinach and butter lettuce in each tent. The farmers advised the crop choice mainly as they grew common crops in the area.

3.5 Data Collection

3.5.1 Observations during site and farm visits. We used the mobile application during each site visit to monitor the pH levels and nutrient solution. After that, we also checked the connectivity and functionality of all components, including the grow light, extractor fan, and fan. The plants were inspected for pests and fungal infections, and any brown or yellow leaves were removed. A considerable amount of helpful information regarding the functionality of the tents was gathered during these site visits. If the farmers happened to be there by coincidence, we would engage in informal conversations with them where they would discuss their experiences using the hydroponic system and grow tents.

3.5.2 Focus groups. A thirty-minute focus group with five farmers was arranged with the Kwazulu-Natal-based farmers. We enquired about their perceptions and experiences with the grow tents and the hydroponic systems. 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 discussions to be recorded. We further ensured that a translator was present to assist with any language barriers. The recording was transcribed, and both the recording 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.

3.5.3 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 the Eastern Cape. The decision to use two WhatsApp groups was based on the concern that the farmers, in many cases, did not know each other; we were concerned that a large WhatsApp group would not only be impersonal but had the potential to overwhelm the farmers. 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 2 Gigabytes of data(2GB) per farmer per month. However, the farmers in Gqeberha elected to refrain from using mobile data as both farms had high-speed internet access.

3.6 Data Analysis

Using Braun and Clarke's approach of inductive thematic analysis [9], the research notes, WhatsApp chats, and focus group transcriptions were analyzed thematically, identifying common and uncommon points of interest that emerged. From here the researchers 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 reported on in our findings.

3.7 Limitations and Ethical Considerations

Ethical clearance for this study was obtained in July 2023 with reference number 3971. All the data generated during this study is stored on the institution's secure data cloud, which is only accessible by the researchers via two-factor authentication (2FA). Any written notes were scanned and digitized, uploaded to the data cloud, and then destroyed. Before any interaction with our farmers, we sought verbal consent. Our research goals and aims were discussed with farmers to identify mutual goals. We worked closely with a translator at both research sites to bridge language barriers, as most of our farmers preferred to engage in their local languages. We affirmed consent in all interactions with the farmers.

It is important to acknowledge that the sensors and grow tent are expensive in the context of our participants. The total cost of a single grow tent, including seedlings and nutrient solution, comes to thirteen thousand South African rands (approximately 694.46 USD). We firmly believe that the cost of innovation should not result in excluding the voices and experiences of developing and often less financially able regions. While the cost of the system was disclosed to the farmers, the farmers did not incur any costs as the researchers decided to provide and donate all the equipment needed for the tents. The researchers worked alongside the farmers from 20 October 2023 to make the system more usable and suitable to their contexts and reduce the costs as far as possible. The study is currently still running and we are still actively working on optimizing the system to better match the farmers needs. Finally, we decided not to remove any deployed grow tents when the study concludes. The grow tents will be donated to the communities, and we will support the farmers and grow tents until they are no longer repairable or needed. We further ensured that the vendors used to procure the equipment for this study also had supply lines at our deployment sites. Finally, the source code, electrical diagrams, and instructions on constructing a grow tent have been provided as open-source resources.

4 RESULTS

4.1 AI-human symbiosis in the field

4.1.1 Becoming a co-grower with technology. In the earlier phases of the study it became quite clear that the grow tent and AI alone would not be able to grow a successful crop. Rural subsistence farmers were crucial throughout the growing period to monitor the crops and mitigate any abnormalities that were observed. Farmers manually inspected the plants for pests and root rot (which occurs when the temperature of the nutrient solution rises too high), nutrient (tip) burn, leaf spot, and edema (which occurs if the hydroponic tent becomes too humid). These plant conditions, if left unattended, can cause significant damage to the plants and even destroy crops. The farmers also manually pruned the plants, removing any brown and yellowing leaves as these leaves can stunt plant growth. There were many other instances we observed where human intervention was needed. For example, the tents were connected to power outlets at the research site offices, and on two occasions, we found that the extension cords were unplugged. This was picked up only when we inspected the tents. The tents went without power for numerous days; luckily, the plants survived once the power was returned to the tents. As a result, several farmers adopted a habit of regularly observing the tents on a weekly basis. This was beneficial because they would take pictures and send messages to the researchers about the plant's progress. If they found anything happening in the tents that they needed help understanding, they asked the researchers the necessary questions to address the problems. Over time the farmers and researchers acknowledged the cooperation required and the bond that grew as farmers developed as co-growers alongside the technology. This became even more evident throughout the focus group discussions when farmers shared their experience of growing food alongside the AI in the tent. At the time of one of the focus groups the farmers and researchers were experiencing a failed crop which resulted in farmers expressing their sadness. One farmer explained they shared with their families that they were very excited that they were finally going to eat the food they grew alongside the AI:

> "I told my children today we are going to be happy because we are going to reap the vegetables, only to come and see that there is nothing to reap."

Another farmer also felt excited knowing that they were going to reap the vegetables, however was disappointed when the crop failed:

> "The plants were so beautiful last week Monday only to find them today. We've been excited to reap only to find that's how they are."

We quickly realized the farmers found it difficult to watch the crops fail but could have benefited from the food grown in the tents. We thus decided to provide the farmers with the same amount of seedlings we planted in the tents, every time we replanted the tents.

4.1.2 Mindset shift – Expanding the status quo. During the study farmers continuously reflected on the traditional farming norms as they adjusted and grew in their knowledge and experience of hydroponic farming. For example, even though the farmers expressed sadness regarding the failed crops (when it occurred), they indicated they were happy with how the hydroponic system worked and saw its potential. One of the farmers explained that the growth rate of the plants in the tents was faster than when they planted in the soil as the butter lettuce in the grow tent matured at 2 weeks as opposed to one month in the soil. This farmer further expressed that a mind shift regarding traditional plant maturing rates and harvest timelines might be needed:

> "The tent it's very fast and hence it is very fast to grow the plants. I think it's because of those nutrients. It means we should reap fast as well."

One of the older farmers further explained that this way of farming was so much easier because aging farmers are struggling with the manual processes of farming due to their age:

> "You can sit on a chair to clean the soil off the seedlings to put in the pipes in the tent. You don't have to bend down to remove weeds. Everything is so easy at our age."

4.1.3 Co-growing and co-researching as a learning experience. Throughout the study the farmers needed to understand how the hydroponic system and the mobile application worked. Moreover, farmers were included in the study not to double-check the functionality of the grow tent but rather as co-growers who could address various circumstances that the AI could not, creating a symbiotic relationship where the grow tent served as a partner the farmers could rely on. Initially, a few farmers experienced difficulties in understanding the technological complexities of the system and figuring out the connection between the plants, artificial intelligence, and the relay box. This was particularly difficult for the older farmers with at least one of the farmers unsure of how to adequately use technology in general. However this farmer relies on the other elderly farmer who in contrast is quite comfortable with technology , this farmer would often send update pictures of how the tent is doing, has no difficulty connecting to WiFi networks or with using social media such as WhatsApp on her phone. These two farmers thus co-grows crops in the tent as a collective rather than individually. The more nervous of the farmers stated :

> "I dont take pictures, I do not know how to send them"

To provide the farmers with a full understanding of the system, the researcher arranged a session where each component of the relay box and artificial intelligence was demonstrated and explained how these components were linked with various elements in the tents. Figure 2 below illustrates the training session that was had by the researcher with the farmers.

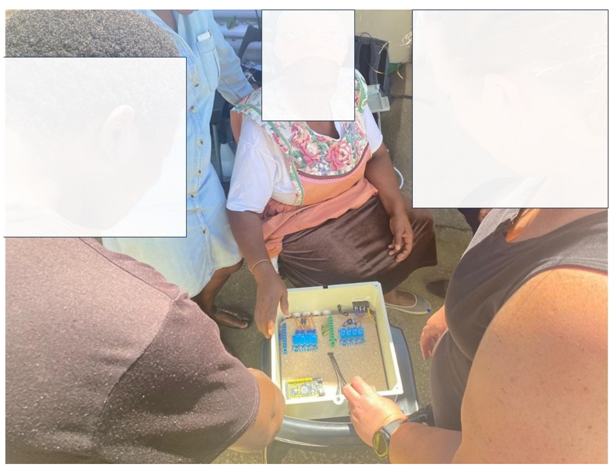

Figure 3: The technology training session with the farmers

One farmer explained how being involved in the study allowed them to gain information about technology and farming that they did not previously have:

> "The information that we have gained in technology and how it works is too much. We wouldn't know that you can monitor the plants via a phone. The technology makes you happy."

Another farmer was happy to be part of the study because of everything that she was learning:

> "I'm happy to be part of this study because I'm learning."

Not only did farmers appreciate the opportunity to grow and learn about alternative farming techniques and how technology could support their goals, they also experienced a sense of connection with fellow farmers. The introduction of the tents resulted in a sense of community amongst the farmers. The farmers expressed that they are now part of a group of farmers who did not know each other before the commencement of the study. However, they can now share their successes, experiences, and difficulties whilst farming.

One farmer expressed this sentiment quite well:

> "I also benefited from that it brought us together and we learn from each other and support each other. So we are now family through this study. That's wonderful."

This was evident in the communications shared on WhatsApp, with the farmers often sharing tips about growing, their own hydroponic sessions and available agricultural opportunities such as leaderships.

4.2 Nature has its way: Accounting for the environment beyond the tent

While our system was trained to maintain the environmental conditions inside the grow tents, due to climate change, various extreme weather conditions, such as powerful storms, extreme temperature fluctuations, and heat, had unintended and unplanned consequences for the grow tents.

4.2.1 The impact of storms, extreme temperature fluctuations, and heat. The change in climate in South Africa has resulted in frequent powerful storms, particularly in the KwaZulu-Natal region. The grow tents in this region were deployed in October 2023, the start of Spring in South Africa, traditionally characterized by storms that occur straight into summer. However, the intensity of these storms has increased drastically in the last year. A storm destroyed a grow tent containing a promising and successful harvest in December. Unfortunately, Sweet Waters in Kwazulu-Natal is now prone to heavy gusts of wind, which blew the tent over completely, flooding the tent, damaging the electronics and AI, and sadly destroying the crop. We later learned that the tent was placed in an area that formed wind tunnels, resulting in strong winds damaging the tent. We subsequently moved the tent to an area that was somewhat protected from adverse weather conditions. We have experienced many storms since then and have not had any more storm damage to the tents. However, although the tents were now in a more protected area, the winds shook the tents, often resulting in power connections being interrupted. In one example, extreme fluctuations in the weather conditions, where the temperature rose from twenty degrees Celsius (60 degrees Fahrenheit) on one day to 40 degrees Celsius (104 degrees Fahrenheit) the very next day, resulted in a rise in humidity in the tents. This led to the tent no longer functioning in an optimal state. Even though the AI was trained to switch on fans, pumps, and other elements in the tent, in this instance, the extractor fan connection was shaken loose, which failed another crop because the AI was unable to switch the extractor fan on. This resulted in the tent and the plants getting wet, which caused leaf spots. Leaf spot is a fungal or bacterial infection that appears as brown spots on plants' leaves. Sometimes, the brown spot is encircled by yellow or reddish halos. These spots can spread to other leaves. The infection eats away at leaf tissue, causing discoloration which can lead to openings in the leaves. Poor circulation and airflow combined with persistently high humidity levels are the most frequent causes of leaf spot[18]. A picture of the leaf spot is shown below.

Figure 4: A: An example of leaf spot. B: An example of nutrient (tip) burn

The extreme heat in February, which is one of the summer months in South Africa, also resulted in the plants taking up more water than usual, which caused very high concentrations of the nutrient solution in the water reservoir. High nutrient solutions results in a nutrient burn, often called tip burn[19]. It also results in nutrient lockout, during which the plant cannot absorb nutrients and will slowly wilt[20]. To address this the researchers and farmers had to monitor the tents and EC levels and manually remove the concentrated nutrient solutions to add fresh water to the reservoir. A picture of the nutrient burn is shown above. Moreover, after a period of extreme heat temperatures in the Kwazulu-Natal province and the humidity in the tents, we found that algae had developed in the water reservoir and pipes of the hydroponic unit. Algae development is common in hydroponic systems as a result of the multiple elements, such as water, light, high temperatures, and the nutrient solution. However, despite its prevalence, algae does not pose a major problem in hydroponic systems. When algae appear before the crops are ready to harvest, treatment can often be delayed until after harvest. Excess algae buildups can result in oxygen deprivation and pH levels that are unsuitable for plants[21]. The algae buildup was closely monitored in the tent and when we lost the crop we treated the algae by cleaning the water reservoir and the pipes of the hydroponic stand.

4.2.2 Pest and Disease Identification and Management. The tents are also not immune to insect infestations, as the control tent in KwaZulu-Natal was infested with aphids after an infected plant from a nursery was placed inside the tent. Aphids are small insects with soft bodies that feed on plants by sucking out their liquid nutrients and are easily overlooked. They come in a range of colors including white, black, brown, gray, yellow, light green, and even pink. The presence of large numbers of aphids can cause severe damage, causing plants to weaken. The key to stopping the aphids from spreading is to control them before they reproduce [22]. While aphid infestations should not result in a crop loss, we, unfortunately, lost a crop because students tasked with monitoring the control tent did not consider the fact that treating the aphid infestation by spraying the plants with a soapy solution, without removing the plants from the hydroponics stand first, would result in the soap ending up in the nutrient solution, poisoning the plants. Soapy solutions are often used by subsistence farmers because it is low cost and easily obtained. However, some knowledge regarding the treatment of pests in a hydroponic tent is needed to ensure that these low-cost solutions can be used effectively and safely. One of the plants in the deployed grow tent was also infested with aphids; luckily, one of the researchers noticed the infected plant before the infestation could spread to the other plants in the tent. The aphids were isolated to one plant, which was subsequently removed. The plants surrounding the infected plant were also removed from the grow tent, sprayed with an organic treatment solution, and placed back in the tent. The tubes of the hydroponic system where the infected plant was planted were wiped using the same solution to remove all possible remaining aphids. Unfortunately, aphid infestations are very difficult to eradicate; however, we are currently (at the time of writing this paper) monitoring for further aphid infestations.

4.3 Beyond the AI: The impact of the quality of equipment and nutrient solutions

Throughout our deployment we recognised the importance of the type of physical infrastructure we had in place beyond how we trained and developed the AI. The type of pump used in the system proved to be crucial. We originally made use of small 300 liters per hour (300L/h) pumps [23] which only work well when the water is kept clean, which is nearly impossible to do in field deployments. The smaller pumps often failed because plant matter would flush out of the hydroponic stand into the reservoir and clog up the pumps. Bigger pumps such as a 620 liter per hour (620L/h) [24] pump, work better because they are less likely to be clogged by plant matter. We further found that the choice of pump was more important than any other element in the grow tent, as a lack of water will result in a failed crop, regardless of how well the AI was trained or the IoT was developed.

There were also occasions when the EC sensors were damaged as they could not be kept outside of a liquid for long periods of time. EC sensors were thus damaged when a grow tent was blown over, or when the pumps failed for an extended period of time. This resulted in the sensors not providing accurate readings, which in turn led to the AI incorrectly classifying the state of the tent and incorrectly adjusting the nutrient solution. It is thus essential that manual digital EC and PH meters are kept in the grow tent to verify

[18]https://heyrooted.com/blogs/common-issues/how-to-treat-leaf-spot
[19]https://blog.growlink.com/how-to-spot-and-resolve-nutrient-burn
[20]https://originhydroponics.com/nutrient-lockout/
[21]https://whyfarmit.com/algae-in-hydroponics/
[22]https://www.almanac.com/pest/aphids
[23]https://www.takealot.com/resun-pond-or-fountain-submersible-water-pump-300l-h/PLID73181066
[24]https://www.takealot.com/waterhouse-fountain-pond-pump-620l-h-with-flow-control-3-core-pl/PLID44935078

that accurate readings can be taken to verify the readings provided by the sensors. As mentioned above, incorrect EC levels will result in crop failures.

We further found the choice of nutrient solution was crucial for successful plant growth. We used different nutrient solutions in the two grow tents deployed in Kwazulu-Natal. This enabled us to watch and compare the growth rate of the plants. We found that one type of nutrient solution [25] provided quicker growth and better sustained the plants. In many cases, choices regarding equipment such as pumps, fans, and elements such as nutrient solutions may prove to be more important than how the AI is trained and developed. Failures in any of these components will result in a failed crop. In this study, to date, AI has not caused any crop failures; in fact, the inclusion of AI has resulted in accelerated plant growth, successful crops, and a reduction in labor.

4.4 Recommendations from farmers

As farmers share their experiences taking part in the study they further provided several recommendations going forward. The farmers requested that the grow tent be connected to the internet so that they could access and monitor the tents remotely. The current system was only accessible through the local WiFi network, which only had a 100-meter range because we had concerns regarding the farmers' data costs and network coverage in the rural areas. However, 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 also recommended that a timetable be drawn up to ensure constant monitoring of the tent. This was suggested because the farmers identified that when things go wrong with the tent, it can happen very quickly, leading to failed crops, which matched the researchers' reasoning. At this point all farmers felt that if they had a formal and agreed upon schedule, there would be constant monitoring. When they monitor the tent and see that something is wrong they can take photos and videos for the researchers to identify the problem.

The farmers further requested that the next iteration of the mobile application should include isiZulu translations for all the features in the application.

5 DISCUSSION

5.1 Lessons learned and design considerations

From our experiences during the seven-month deployments of these tents, we can provide the following lessons learned and design considerations: In line with Bhatnagar et al. [8], Thilakarathne et al. [58], we found that protecting the tents from adverse weather conditions in the field proved complicated. While this statement seems obvious, knowing how the elements affect different deployment site areas is often challenging. We found that placing the grow tents in an undercover area, with at least a backing wall, is sufficient to protect the tents from storms. It is also important to secure the electronic connection of the elements in the tent to withstand the effects of storms on the tent. We recommend that researchers observe the deployment site and have a more holistic understanding on how the AI is being embedded in the larger crop growing ecosystem. Historical weather patterns are also important [49, 52], particularly in countries experiencing extreme heat. Many of the challenges we faced in January and February in Africa would not be as devastating in months that are not in the heart of summer. In our experience, we often reacted to erratic weather conditions rather than planning for them. We therefore recommend that researchers either carefully monitor the weather forecast or connect the tent to a weather forecasting service to enable the AI to "plan" for extreme heat or cold. This can be achieved by programming the AI and microcontroller to act according to the weather forecast. Our system would have greatly benefited if the system "knew" a temperature spike was coming, we could have programmed the microcontroller and AI to not pump nutrients on hot days and to turn on all the fans in the tent.

Our findings further highlight the fact that the water in the reservoir needs to be kept cool. This can be achieved with expensive water cooling systems, often not feasible for small-scale farmers; we recommend placing water-filled, frozen plastic bottles in the reservoir on hot days. Hydroponic systems are particularly prone to the spread of fungal infections, especially if the plants share a common water reservoir [40]. Further, these systems (even in a controlled environment such as a grow tent) are not immune to pests. In our case, a single microcontroller and ML algorithm could only address some challenges while farming hydroponically. Some form of automated or human-based pest control mechanisms should be included in the design and planning of these systems. While many different models can be trained, such as the CNN recommended for pest control by Ramachandran et al. [47], and the Linear Regressor to better control nutrient solutions recommended by Kaewwiset and Yooyativong [31]. Including diverse technologies in a single deployment to completely automate the system will result in costs that will be unmanageable for small-scale farmers [7, 46]. It is, therefore, essential to keep humans in the loop and work with farmers to design a system that can complement and reduce their workload rather than trying to automate the entire plant growth process. Our findings indicated that managing the water levels and nutrient solution proved to be complex during the summer months and often required human intervention. Automating this process would require a sophisticated water cycling system and water level sensors to avoid overfilling the reservoir and flooding the tent.

Implementing such a system will be complex, and the system's electricity consumption would also need to be carefully considered as LMIC countries often have poor electricity access, often experience power outages that can last many days and often pay more for electricity [32, 38]. In our case, humans proved to be crucial. A simple mistake such as unplugging these systems from their power supply can be devastating. These tents require constant human and non-human monitoring as challenges arise quickly and can just as quickly have adverse effects on the crop [11, 39, 43]. It would be beneficial to equip the grow tents and mobile application with video capability to assist in remote monitoring. While it is true that

[25] https://www.seedsforafrica.co.za/products/terra-aquatica-pro-organic-grow-hydroponic-soil-nutrients?variant=39717487050901

mobile data in South Africa is expensive [42], the participants in our study requested that the tents be connected to the internet to enable the above-mentioned remote monitoring. However, we recommend a hybrid system that allows the farmer to choose whether they wish to use data when they are within range of the local WiFi network provided by the tent. The inclusion of internet activity will further ensure that the system can notify farmers should any of the elements in the tent cease to function Hassan et al. [23].

Finally, working with rural farmers who carefully and lovingly tend to their corps can be difficult as it is hard for the farmers to witness corp failures. It is crucially important that researchers take the time to build the necessary empathy [59] and to handle these occurrences with care. In our case, we opted to provide farmers with additional seedlings for every crop we planted in the tents to ensure they could grow a crop should the crop in the tents fail.

5.2 Possibilities and Limitations

Regardless of the challenges we experienced during our deployment, we found the grow tents promising. In line with the findings of Dutta et al. [18] we can also report that including the AI to monitor and control the elements in the tent resulted in accelerated crop growth. The system further allowed the farmers to cultivate crops that, due to climate change, have become difficult to grow using traditional farming methods [41]. The majority of the older farmers who elected to take part in this study consider themselves to be "community growers" who provide food to community members in need. In our findings, we reported that the tent reduces labor for the older farmers, enabling them to grow food for their communities longer as they no longer have to carry heavy watering cans or bend down to weed. In agreement with M et al. [35] we can also report that the tents use less water than traditional crops and can grow 72 plants in a small space.

However, the tents have limitations that need to be considered. Failures in the functioning of the tent, whether caused by extreme heat, storms, or human error, will lead to rapid crop failures, often within days. Fluctuations in the nutrient solutions can lead to bitter-tasting plants, and crop failures are hard on the morale of both the researchers and the farmers. This study further included three farmers over the age of 60; while age alone is not an indicator of successful technology adoption [14], the older farmers did initially struggle to connect to the local WiFi network and use the application to monitor the tents.

Finally, we agree with the findings of Mohan et al. [40], who explain that the challenge with encouraging AI implementation in agriculture is not related to the ability of agriculture science but rather the variance in physical conditions, which makes the deployment and testing of these systems difficult.

6 FUTURE WORK

Further research will entail the integration of a Convolutional Neural Network (CNN) to allow for pest and fungal infection detection. We intend for this technology to facilitate the timely identification of pests and fungal infections, thereby promoting the implementation of preventative measures to minimize crop loss. A web camera will be installed in the tents, which will be connected to the Internet to enable this functionality and better remote management. As previously mentioned, we intend to investigate how to connect the tents to a weather forecasting service to allow the AI to "plan" for extreme heat or cold. This will be achieved by programming the AI and microcontroller to act according to the weather forecast. Finally, we plan to train a Linear Regression (LR) model to determine the exact amount of nutrient solution to supply for the given EC readings.

7 CONCLUSION

In this study, we found that deploying AI and IoT hydroponic grow tents in the field highlighted many complexities that should be discussed in research papers. These complexities include pest infestations, extreme weather conditions, and the choice of equipment and nutrient solutions used, all of which can adversely affect the crops and functioning of these systems. From our experience, we provide technological and non-technical design considerations such as carefully considering the physical placement of hydroponic systems to avoid storm damage, considering the seasons for deployments as some seasons can provide more complexity than others, and securing the electrical connections of the elements in the tent. We further highlight that AI aimed at agriculture settings requires frequent human intervention and should be designed to assist farmers rather than automate the entire plant growth process. We finally highlight that while this deployment provided many lessons, AI and IoT-enabled hydroponic grow tents show promise in addressing food security, if implemented correctly.

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REFERENCES

[1] R. K. Agrawal, M. P. Tripathi, A. Verma, G. L. Sharma, and D. Khalkho. 2020. Hydroponic systems for cultivation of horticultural crops: A review. *Journal of Pharmacognosy and Phytochemistry* 9, 6 (2020), 2083–2086. https://www.phytojournal.com/archives/2020.v9.i6.13271/hydroponic-systems-for-cultivation-of-horticultural-crops-a-review Publisher: AkiNik Publications.

[2] Johanna Alberts, John Rheeder, Wentzel Gelderblom, Gordon Shephard, and Hester-Mari Burger. 2019. Rural subsistence maize farming in South Africa: Risk assessment and intervention models for reduction of exposure to fumonisin mycotoxins. *Toxins* 11, 6 (2019), 334.

[3] Michael Aliber and Tim GB Hart. 2009. Should subsistence agriculture be supported as a strategy to address rural food insecurity? *Agrekon* 48, 4 (2009), 434–458.

[4] Melchizedek I Alipio, Allen Earl M Dela Cruz, Jess David A Doria, and Rowena Maria S Fruto. 2017. A smart hydroponics farming system using exact inference in Bayesian network. In *2017 IEEE 6th Global Conference on Consumer Electronics (GCCE)*. IEEE, 1–5.

[5] Prabadinata Atmaja and Nico Surantha. 2022. Smart hydroponic based on nutrient film technique and multistep fuzzy logic. *International Journal of Electrical and Computer Engineering* 12, 3 (2022), 3146.

[6] Fabrizio Balducci, Donato Impedovo, and Giuseppe Pirlo. 2018. Machine learning applications on agricultural datasets for smart farm enhancement. *Machines* 6, 3 (2018), 38.

[7] Vivek Bhatnagar, Gulbir Singh, Gautam Kumar, and Rajeev Gupta. 2020. INTERNET OF THINGS IN SMART AGRICULTURE: APPLICATIONS AND OPEN CHALLENGES. *Int. J. Stud. Res. Technol. Manage* (Jan. 2020). https://doi.org/10.18510/ijsrtm.2020.812

[8] Vivek Bhatnagar, Gulbir Singh, Gautam Kumar, and Rajeev Gupta. 2020. Internet of thingsin smart agriculture: applications and open challenges. *Int. J. Stud. Res. Technol. Manage.* 8, 1 (2020), 11–17.

[9] Virginia Braun, Victoria Clarke, Nikki Hayfield, Louise Davey, and Elizabeth Jenkinson. 2023. Doing reflexive thematic analysis. In *Supporting Research in Counselling and Psychotherapy: Qualitative, Quantitative, and Mixed Methods Research.* Springer, 19–38.

[10] Eric Brewer, Michael Demmer, Bowei Du, Melissa Ho, Matthew Kam, Sergiu Nedevschi, Joyojeet Pal, Rabin Patra, Sonesh Surana, and Kevin Fall. 2005. The case for technology in developing regions. *Computer* 38, 6 (2005), 25–38.

[11] Cheng-Hung Chen, Shiou-Yun Jeng, and Cheng-Jian Lin. 2021. Fuzzy Logic Controller for Automating Electrical Conductivity and pH in Hydroponic Cultivation. *Applied Sciences* 12, 1 (Dec. 2021), 405. https://doi.org/10.3390/app12010405

[12] V KIRUI Cherotich, OSENI Saidu, and B OMEDO Bebe. 2012. Access to climate change information and support services by the vulnerable groups in semi-arid Kenya for adaptive capacity development. *African Crop Science Journal* 20 (2012), 169–180.

[13] Rajiv Chopra. 2018. *Software quality assurance: a self-teaching introduction.* Mercury Learning and Information.

[14] Sara J Czaja, Chin Chin Lee, Sankaran N Nair, and Joseph Sharit. 2008. Older adults and technology adoption. In *Proceedings of the human factors and ergonomics society annual meeting*, Vol. 52. SAGE Publications Sage CA: Los Angeles, CA, 139–143.

[15] J A Dela Vega, J A Gonzaga, and L A Gan Lim. 2021. Fuzzy-based automated nutrient solution control for a hydroponic tower system. *IOP Conference Series: Materials Science and Engineering* 1109, 1 (March 2021), 012064. https://doi.org/10.1088/1757-899X/1109/1/012064

[16] Kaitano Dube, Godwell Nhamo, and David Chikodzi. 2022. Flooding trends and their impacts on coastal communities of Western Cape Province, South Africa. *GeoJournal* 87, Suppl 4 (2022), 453–468.

[17] Neha Dubey and Vaibhav Nain. 2020. Hydroponic— The Future of Farming. *International Journal of Environment, Agriculture and Biotechnology* 4, 4 (2020), 857–864. https://doi.org/10.22161/ijeab.54.2

[18] Monica Dutta, Deepali Gupta, Sangeeta Sahu, Suresh Limkar, Pawan Singh, Ashutosh Mishra, Manoj Kumar, and Rahim Mutlu. 2023. Evaluation of Growth Responses of Lettuce and Energy Efficiency of the Substrate and Smart Hydroponics Cropping System. *Sensors* 23, 4 (2023), 1875.

[19] Tayengwa Dyke, Tirivangasi Happy Mathew, and Rankoana Sejabaledi Agnes. 2020. Rural community perceptions on the impact of climate change on subsistence farming: Mutoko community in Zimbabwe. *e-BANGI* 17, 7 (2020), 89–104.

[20] Jean Luc ERERO. 2023. Impact of loadshedding in South Africa: A CGE analysis. *Journal of Economics and Political Economy* 10, 2 (2023), 78–94.

[21] Mathawee Fuangthong and Part Pramokchon. 2018. Automatic control of electrical conductivity and PH using fuzzy logic for hydroponics system. In *2018 International Conference on Digital Arts, Media and Technology (ICDAMT).* IEEE, 65–70.

[22] Bob Garfield. 2003. And now a few words from me : advertisings leading critic lays down the law, once and for all. (2003). https://digital.library.tu.ac.th/tu_dc/frontend/Info/item/dc:20733 Accepted: 2012-06-17T01:51:09Z ISBN: 9780071403160 Number: 20733 Publisher: McGraw-Hill.

[23] Aveen Uthman Hassan, Mu'azu Jibrin Musa, Yahaya Otuoze Salihu, Abubakar Abisetu Oremeyi, and Fatima Ashafa. 2022. Artificial Intelligence Based Soilless Agriculture System Using Automatic Hydroponics Architecture. In *International Conference on Intelligent Systems and Machine Learning.* Springer, 117–130.

[24] Markus Hittmeir, Andreas Ekelhart, and Rudolf Mayer. 2019. On the Utility of Synthetic Data: An Empirical Evaluation on Machine Learning Tasks. In *Proceedings of the 14th International Conference on Availability, Reliability and Security.* ACM, Canterbury CA United Kingdom, 1–6. https://doi.org/10.1145/3339252.3339281

[25] Isaac Holeman, Edwin Blake, Melissa Densmore, Maletsabisa Molapo, Fiona Ssozi, Elizabeth Goodman, Indrani Medhi Thies, and Susan Wyche. 2017. Co-design across borders special interest group. In *Proceedings of the 2017 CHI conference extended abstracts on human factors in computing systems.* 1318–1321.

[26] Hilary Hutchinson, Wendy Mackay, Bo Westerlund, Benjamin B. Bederson, Allison Druin, Catherine Plaisant, Michel Beaudouin-Lafon, Stéphane Conversy, Helen Evans, Heiko Hansen, Nicolas Roussel, and Björn Eiderbäck. 2003. Technology Probes: Inspiring Design for and with Families. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Ft. Lauderdale, Florida, USA) *(CHI '03).* Association for Computing Machinery, New York, NY, USA, 17–24. https://doi.org/10.1145/642611.642616

[27] Elijah G Ikrang, Precious O Ehiomogue, and Unwana I Udoumoh. 2022. HYDROPONICS IN PRECISION AGRICULTURE–A REVIEW. *Annals of the Faculty of Engineering Hunedoara* 20, 2 (2022), 143–148.

[28] James Jordon, Lukasz Szpruch, Florimond Houssiau, Mirko Bottarelli, Giovanni Cherubin, Carsten Maple, Samuel N Cohen, and Adrian Weller. 2022. Synthetic Data–what, why and how? *arXiv preprint arXiv:2205.03257* (2022).

[29] Caneel K Joyce. 2009. *The blank page: Effects of constraint on creativity.* University of California, Berkeley.

[30] Damion Joyner and Sarina Till. 2023. A simulated study exploring and testing Fuzzy Logic AI and IoT-enabled hydroponic dosing systems aimed at rural subsistence farmers in South Africa. In *Proceedings of the 6th ACM SIGCAS/SIGCHI Conference on Computing and Sustainable Societies.* 12–22.

[31] Theeramet Kaewwiset and Thongchai Yooyativong. 2017. Electrical conductivity and pH adjusting system for hydroponics by using linear regression. In *2017 14th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON).* IEEE, 761–764.

[32] Makoto Kanagawa and Toshihiko Nakata. 2008. Assessment of access to electricity and the socio-economic impacts in rural areas of developing countries. *Energy policy* 36, 6 (2008), 2016–2029.

[33] Azimbek Khudoyberdiev, Shabir Ahmad, Israr Ullah, and Dohyeon Kim. 2020. An Optimization Scheme Based on Fuzzy Logic Control for Efficient Energy Consumption in Hydroponics Environment. *Energies* 13 (Jan. 2020), 289. https://doi.org/10.3390/en13020289

[34] JVN Lakshmi and KS Hemanth. [n. d.]. Hydroponic Farming using Leafy Green Machines for Agriculture by Applying Deep Learning Methods. ([n. d.]).

[35] Dutta M, Gupta D, Sahu S, Limkar S, Singh P, Mishra A, Kumar M, and Mutlu R. 2023. Evaluation of Growth Responses of Lettuce and Energy Efficiency of the Substrate and Smart Hydroponics Cropping System. *Sensors (Basel, Switzerland)* 23, 4 (Feb. 2023). https://doi.org/10.3390/s23041875 Publisher: Sensors (Basel).

[36] Tshepo S. Masipa. 2017. The impact of climate change on food security in South Africa: Current realities and challenges ahead. *Jàmbá : Journal of Disaster Risk Studies* 9, 1 (2017). https://doi.org/10.4102/jamba.v9i1.411 Publisher: AOSIS.

[37] AJ Meintjes and PR Smit. 2017. Variables influencing the success of subsistence farming: is business management a solution? *Journal of Contemporary Management* 14, 1 (2017), 1165–1193.

[38] Justice Tei Mensah. 2024. Jobs! Electricity shortages and unemployment in Africa. *Journal of Development Economics* 167 (2024), 103231.

[39] GW Michael, FS Tay, and YL Then. 2021. Development of automated monitoring system for hydroponics vertical farming. In *Journal of Physics: Conference Series*, Vol. 1844. IOP Publishing, 012024.

[40] S Sai Mohan, Regatti Venkat, S Rahaman, M Vinayak, and B Hari Babu. 2023. Role of AI in agriculture: applications, limitations and challenges: A review. *Agricultural Reviews* 44, 2 (2023), 231–237.

[41] John F. Morton. 2007. The impact of climate change on smallholder and subsistence agriculture. *Proceedings of the National Academy of Sciences* 104, 50 (Dec. 2007), 19680–19685. https://doi.org/10.1073/pnas.0701855104 Company: National Academy of Sciences Distributor: National Academy of Sciences Institution: National Academy of Sciences Label: National Academy of Sciences Publisher: Proceedings of the National Academy of Sciences.

[42] Dumisani Moyo and Allen Munoriyarwa. 2021. 'Data must fall': mobile data pricing, regulatory paralysis and citizen action in South Africa. *Information, Communication & Society* 24, 3 (Feb. 2021), 365–380. https://doi.org/10.1080/1369118X.2020.1864003 Publisher: Routledge _eprint: https://doi.org/10.1080/1369118X.2020.1864003.

[43] Mahdi Musa, Audu Mabu, Falmata Modu, Adam Adam, and Farouq Aliyu. 2022. Automated Hydroponic System using Wireless Sensor Networks. *Modu, F., Adam, A., Aliyu, F., Mabu, A., & Musa, M.(2020). A survey of smart hydroponic systems. Advances in Science, Technology and Engineering Systems Journal* 5, 1 (2022), 233–248.

[44] Jumras Pitakphongmetha, Nathaphon Boonnam, Siriwan Wongkoon, Teerayut Horanont, Deeprom Somkiadcharoen, and Jiranuwat Prapakornpilai. 2016. Internet of things for planting in smart farm hydroponics style. In *2016 International Computer Science and Engineering Conference (ICSEC).* IEEE, 1–5.

[45] John Carlo V Puno, Jenskie Jerlin I Haban, Jonnel D Alejandrino, Argel A Bandala, and Elmer P Dadios. 2020. Design of a nutrient film technique hydroponics system with fuzzy logic control. In *2020 IEEE REGION 10 CONFERENCE (TENCON).* IEEE, 403–408.

[46] Sameer Qazi, Bilal A Khawaja, and Qazi Umar Farooq. 2022. IoT-equipped and AI-enabled next generation smart agriculture: A critical review, current challenges and future trends. *IEEE Access* 10 (2022), 21219–21235.

[47] Divya Ramachandran, John Canny, Prabhu Dutta Das, and Edward Cutrell. 2010. Mobile-izing health workers in rural India. In *Proceedings of the 28th international conference on Human factors in computing systems - CHI '10.* ACM Press, Atlanta, Georgia, USA, 1889. https://doi.org/10.1145/1753326.1753610

[48] S. V. S. Ramakrishnam Raju, Bhasker Dappuri, P. Ravi Kiran Varma, Murali Yachamaneni, D. Marlene Grace Verghese, and Manoj Kumar Mishra. 2022. Design and Implementation of Smart Hydroponics Farming Using IoT-Based AI Controller with Mobile Application System. *Journal of Nanomaterials* 2022 (July 2022). https://doi.org/10.1155/2022/4435591 Publisher: Hindawi.

[49] Sejabaledi Agnes Rankoana. 2022. Indigenous knowledge and innovative practices to cope with impacts of climate change on small-scale farming in Limpopo Province, South Africa. *International Journal of Climate Change Strategies and Management* 14, 2 (2022), 180–190.

[50] Simone Salerno. 2022. Micromlgen. https://pypi.org/project/micromlgen/

[51] Elizabeth B-N Sanders and Pieter Jan Stappers. 2008. Co-creation and the new landscapes of design. *Co-design* 4, 1 (2008), 5–18.

[52] Juan Sesmero, Jacob Ricker-Gilbert, and Aaron Cook. 2018. How do African farm households respond to changes in current and past weather patterns? A structural panel data analysis from Malawi. *American Journal of Agricultural Economics* 100, 1 (2018), 115–144.

[53] Qange Siphesihle and Mdoda Lelethu. 2020. Factors affecting subsistence farming in rural areas of nyandeni local municipality in the Eastern Cape Province. *South African Journal of Agricultural Extension* 48, 2 (2020), 92–105.

[54] Q. Siphesihle and M. Lelethu. 2020. Factors affecting subsistence farming in rural areas of nyandeni local municipality in the Eastern Cape Province. *South African Journal of Agricultural Extension* 48, 2 (2020), 92–105. https://doi.org/10.17159/2413-3221/2020/v48n2a540 Publisher: South African Society for Agricultural Extension (SASAE).

[55] Karanya Sitdhisanguan, Nopporn Chotikakamthorn, Ajchara Dechaboon, and Patcharaporn Out. 2012. Using tangible user interfaces in computer-based training systems for low-functioning autistic children. *Personal and Ubiquitous Computing* 16, 2 (Feb. 2012), 143–155. https://doi.org/10.1007/s00779-011-0382-4 Company: Springer Distributor: Springer Institution: Springer Label: Springer Number: 2 Publisher: Springer-Verlag.

[56] Herry Suhardiyanto, Kudang B. Seminar, Yudi Chadirin, and Budi I. Setiawan. 2001. Development of a ph Control System for nutrient solution in EBB and Flow Hydroponic Culture Based on Fuzzy Logic. *IFAC Proceedings Volumes* 34, 11 (Aug. 2001), 87–90. https://doi.org/10.1016/S1474-6670(17)34111-3

[57] Fredy Susanto, Ni Kadek Suryani, Putu Darmawan, Komang Prasiani, and I Made Satria Ramayu. 2021. Comprehensive Review on Automation in Hydroponic Agriculture Using Machine Learning and IoT. In *RSF Conference Series: Engineering and Technology*, Vol. 1. 86–95.

[58] Navod Thilakarathne, Hayati Yassin, Muhammad Abu Bakar, and Pg Emeroylariffion Abas. 2021. Internet of Things in Smart Agriculture: Challenges, Opportunities and Future Directions. 1–9. https://doi.org/10.1109/CSDE53843.2021.9718402

[59] Sarina Till, Melissa Densmore, Toshka Lauren Coleman, and Nervo Verdezoto Dias. 2021. Poster: Lessons from Doing Fieldwork with Bandwidth-constrained communities Online. In *Proceedings of the 4th ACM SIGCAS Conference on Computing and Sustainable Societies* (Virtual Event, Australia) *(COMPASS '21)*. Association for Computing Machinery, New York, NY, USA, 445–448. https://doi.org/10.1145/3460112.3471979

[60] Sarina Till, Jaydon Farao, Toshka Lauren Coleman, Londiwe Deborah Shandu, Nonkululeko Khuzwayo, Livhuwani Muthelo, Masenyani Oupa Mbombi, Mamare Bopane, Molebogeng Motlhatlhedi, Gugulethu Mabena, et al. 2022. Community-based co-design across geographic locations and cultures: methodological lessons from co-design workshops in South Africa. In *Proceedings of the Participatory Design Conference 2022-Volume 1*. 120–132.

[61] Sarina Till, Mirriam Mkhize, Jaydon Farao, Londiwe Deborah Shandu, Livhuwani Muthelo, Toshka Lauren Coleman, Masenyani Mbombi, Mamara Bopape, Sonja Klingberg, Alastair van Heerden, et al. 2023. Digital Health Technologies for Maternal and Child Health in Africa and Other Low-and Middle-Income Countries: Cross-disciplinary Scoping Review With Stakeholder Consultation. *Journal of Medical Internet Research* 25 (2023), e42161.

[62] R. Velazquez-Gonzalez, T. Gomez-Lemus, and J. Rodriguez-Resendiz. 2017. A pH process control embedded on a PLC using Fuzzy Logic. In *2017 XIII International Engineering Congress (CONIIN)*. IEEE, Santiago de Queretaro, Mexico, 1–6. https://doi.org/10.1109/CONIIN.2017.7968179

[63] Desta Yolanda, Hilwadi Hindersah, Febrian Hadiatna, and Muhammad Agus Triawan. [n. d.]. Implementation of Real-Time Fuzzy Logic Control for NFT-Based Hydroponic System on Internet of Things Environment. ([n. d.]).

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