NkhukuProbe: Using a Sensor-Based Technology Probe to Support Poultry Farming Activities in Malawi

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ABSTRACT

Poultry farming is a significant income-generating activity in sub-Saharan African (SSA) households. Poultry farmers frequently have to overcome extreme environmental conditions to maintain their chickens' wellbeing. Prior research has proposed automating poultry farming activities to control environmental conditions (e.g., temperature and humidity). However, these interventions have never been implemented, in this context, to understand how they would work and participants' perceptions. Further, chicken coops in SSA have different configurations that would make technology automation difficult. To explore how technology can be used to address this problem, we worked with local collaborators to design and deploy "NkhukuProbe"—a low-cost sensor-based technology that poultry farmers can interact with via USSD (Unstructured Supplementary Service Data) to monitor and adjust chicken coop conditions. First, we conducted a review of related work on poultry farming in SSA and a pilot study with poultry farming experts. Findings from this work guided the design of NkhukuProbe. Then, we deployed NkhukuProbe in 15 Malawian households for one month. The goals of our deployment were to understand participants' experiences using NkhukuProbe and to learn about other ways of using sensors in this context. To achieve these goals, we used interview, diary, observation and data logging to collect data throughout the deployment. Our findings suggest that a technology probe's approach unveiled different opportunities for using sensors to support poultry farming in SSA. Further, NkhukuProbe motivated participants to think of other ways of using sensors. We present design implications based on these findings and offer new perspectives on the role of technology in supporting poultry farming activities.

CCS CONCEPTS

• **Human-centered computing**; • **Human computer interaction (HCI)**;

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1 INTRODUCTION

Poultry farming provides a significant source of food and income in sub-Saharan Africa (SSA) [2, 4]. Households that practice poultry farming make more than double the income of households that do not [4]. The income generated from poultry farming is used to acquire household property (e.g., furniture and radios) and to pay for children's education [2]. Despite these benefits, poultry farmers struggle to fully benefit from their activities because of adverse environmental conditions (e.g., high temperature that cause heat stress). These adverse conditions reduce chickens' food intake, body weight, and contribute to high mortality rate [36]. While poultry farmers have their own measures of managing poultry farming activities, they lack tools that provide real-time chicken coop conditions. Our prior research suggests that people in SSA are interested to use sensor-based technologies to support their poultry farming practices [9, 10].

In this article, we investigate the potential for using sensor-based technologies to support poultry farming practices. These questions guided our research: how can sensor-based technologies support poultry farming activities in Malawi?; and, what are the farmers' perceptions of sensor-based technologies? To answer these questions, we conducted a literature review, and pilot interviews with domain experts to understand the challenges that poultry farmers encounter when managing their coops. We found that temperature, humidity, and light are three important environmental factors that poultry farmers want to monitor. Temperature is especially challenging in SSA, where summer temperatures can reach over 40°C (12°C than the average temperature). These findings inspired the design of NkhukuProbe ("nkhuku is a Chichewa[1] name for chicken), a low-cost sensor-based technology probe that allows poultry farmers to monitor their coops' environmental conditions. Previously proposed sensor-based systems have automatically modified coops by opening windows and activating fans when poor environmental

[1]Chichewa is a national language spoken in Malawi

conditions arise [39]. However, each coop is different, so creating such a system often requires special equipment for mechanical actuation. Instead, NkhukuProbe provides real-time data and alerts to poultry farmers through a USSD service[2] so that they can adjust the coop conditions themselves. We deployed NkhukuProbe in 15 Malawian households for a month. We used a combination of observations, diaries, interviews, and data logging methods to learn about participants' experiences using the probe.

Our findings suggest that NkhukuProbe can support participants' desires to monitor their chicken coops' conditions, such as temperature, lighting and humidity. This presents an opportunity for poultry farmers to save time and resources that are used in poultry farming. A reduction in the use of poultry farming resources (e.g., charcoal) can potentially reduce harmful environmental impacts. NkhukuProbe did not replace participants' existing poultry farming practices but rather reinforced them by providing awareness benefits to participants. The technology probe's open-ended design inspired participants to think about other ways of improving environmental conditions in their chicken coops (e.g., inspecting their coops' roofing to identify leaks that might affect humidity). Further, NkhukuProbe allowed participants to experiment with it, demonstrate it to their neighbors, and use it beyond their chicken coops (e.g., their main households). These observations draw attention to more opportunities for using sensor-based technologies in SSA homes (e.g., sensors as a platform for teaching poultry farmers).

This paper makes these contributions to HCI: (1) findings from a deployment study that suggest that sensor-based technologies can support Malawian farmers' poultry practices; and (2) implications for designing sensor-based technologies to support poultry farming activities in Malawi.

The rest of the paper is structured as follows: We review related research. Then, we present an overview of our research approach. Following this, we describe phase I of the study (formative research), and subsequently present its findings. Next, we provide rationale about NkhukuProbe's design. After this section, we describe the methods we used in our phase II (NkhukuProbe deployment) followed by a section on how we analysed data. Next, we present findings from our preliminary interviews and observations before NkhukuProbe deployment, and then our findings after the deployment. These findings motivate a discussion about broader implications of our research. Then, we provide a section on limitations and future work. We end the paper with a conclusion section.

2 LITERATURE REVIEW

Sensors-based systems are more readily available than ever before. In this section, we provide an overview of the various settings in which sensors have been incorporated into people's lives: in SSA and for poultry farming practices.

2.1 Sensors in Sub-Saharan Africa

The proliferation of smartphones has positively influenced the application of sensors for various activities in SSA. The Global System for Mobile Communications (GSMA) estimates that the fraction of SIM connections in SSA will rise to 86% by 2025, of which 65% will come from smartphones [14]. Beyond the access to information and communication that smartphones provide, researchers are exploring ways that smartphones can be used for point-of-care diagnostics [21]. For instance, smartphone cameras are being used to facilitate the documentation and interpretation of rapid diagnostic tests [13, 38]. Wood *et al.* [49] provide commentary on how smartphones have been used as a power and communication hub for externally connected sensors like photodiodes or ultrasound probes.

Beyond mobile health, sensors are also being used in embedded devices to solve human-centered and environmental issues in SSA. Rapid urbanization and population growth have led to elevated urban air pollution levels in some countries [29], which has driven the need for air quality monitors to be mounted on streetlight poles and rooftops [15]. Sensors are also being used in rural areas to increase the supply of high-quality livestock feed. For example, Modroño *et al.* [31] demonstrated how handheld near-infrared sensors can be used to analyze the nutritional composition of feed, while Hwang *et al.* [20] proposed a system that uses a combination of a smartphone app, a closed-circuit television (CCTV), and environmental sensors for monitoring feed distribution systems. Balehegn *et al.* [3] note that although technologies like these exist for addressing issues with livestock feed management, their adoption has been stifled by infrastructural and sociocultural factors (e.g., limited awareness and governmental regulation). Further, rural communities in SSA tend to have limited access to smartphones—in Malawi, only 7% of the population have access to smartphones [34]. In this work, we look beyond these broad societal challenges that preclude widespread adoption; instead, we investigate how people in rural SSA interact with a sensor-based system that supports an everyday task like poultry farming.

2.2 Using Sensors to Support Poultry Farming in Sub-Saharan Africa

Researchers have proposed different sensor-based technologies to support poultry farming in SSA, many that monitor and modify the environment within chicken coops [1, 17, 23, 39]. The major conditions that affect chicken production are temperature and humidity [33]. Chickens thrive at an environment that is 33°C with a relative humidity of 50%. However, many places in SSA experience high humidity and temperatures that can exceed these conditions [16]; this makes it difficult for farmers to realize maximum egg production. Phiri and Phiri [39] proposed integrating temperature sensing into a system that also detected intruders' presence within a chicken coop. Poultry farmers received alerts via a mobile app, SMS, or web-based application. Afeez *et al.* proposed a similar system to regulate environmental factors automatically [1]. Although both systems address poultry farming challenges, they were never evaluated "in the wild"; that is, in a poultry farm to understand how farmers would actually use them, and whether it would improve their poultry farming practices.

Lighting is also important for chicken rearing. Proper lighting controls physiological and behavioral processes during chicken development, stimulates feed intake, and facilitates chicken coop inspection [43]. The optimal light duration in chicken coops depends

[2]USSD Service is a communication protocol that is used by GSM network to communicate with mobile network provider servers. The service uses quick codes that a user dial on their phone to receive feedback from the server. Unlike SMS, users interact with the server through a series of menus in real-time.

on a chicken's age; for laying chickens (chickens raised for egg production), it is recommended that chicken coops have 15 hours of constant light [43]. Unlike temperature and humidity, the importance of light is not as intuitive among farmers and is therefore less likely to be a parameter that inexperienced farmers consider monitoring [43]. Furthermore, manually controlling chicken coop lighting to comply with this specification can be difficult because farmers might forget to alter the lights. Sensor-based technologies can potentially address this challenge by automatically controlling lighting conditions in chicken coops.

Our research builds upon these prior studies by exploring how farmers in SSA would interact with a sensor-based technology (in participants' natural setting environment) to support their poultry farming activities. Our formative research findings suggest that poultry farmers in this context have unique coop configurations and tools they use to monitor activities in their chicken coops. This motivated us to design a "technology probe" to allow them to use it based on their needs. Technology probes are open-ended and co-adaptive—they allow users to creatively adapt them to their own needs [19]. Rather than automatically driving a change to the chicken coop itself, our probe, provides real-time data to poultry farmers so that they can make changes themselves.

3 RESEARCH APPROACH

We used technology probes and other qualitative methods in our research. We used technology probes, because they are especially useful during early stages of the design process and for introducing users to new technologies [19]. Poultry farmers in SSA rarely—if ever—use sensor-based technologies to support their poultry farming activities. Thus, technology probes helped us introduce sensors for poultry farming in SSA. Technology probes do not only allow users to be part of the design process, but they also inspire them to think of other ways of using new technologies [19]. The open-ended nature of a probes approach allows users to interact with them based on their needs [10]. Our approach allowed us to explore the role of sensor-based technologies for poultry farming, as well as participants' perceptions and experiences using the probe. One of the goals of technology probes is an engineering goal to field-test technologies in a real-world setting [19]. While prior studies [1, 39, 40] have proposed sensor-based solutions for poultry farming in SSA, they were never tested in real-world poultry farms. We build on this prior research and explore the potential for using sensor-based solutions in SSA. NkhukuProbe collected quantitative data by itself through data logging. To collect data about participants' perceptions and experiences using the probe, we used qualitative methods i.e., interviews, diaries, and observation.

We conducted this research during the COVID-19 pandemic (August to December 2020). Our study was approved by Michigan State University's (MSU) Institutional Review Board. COVID-19 safety protocols (wearing masks and social distancing) were followed during our deployment.

4 PHASE I: FORMATIVE RESEARCH

To understand the domain of poultry farming, we reviewed the aforementioned research on poultry farming in SSA. We then conducted pilot interviews with poultry farming researchers to understand the factors that influence poultry health, the tools that farmers use in SSA to support poultry farming activities, and how sensors are currently being used in poultry farming. The first author also draws from his 20+ years of experience living in Malawi; these experiences, especially his encounters with poultry farming influenced the project, inspired our intervention, and allowed him to empathize with study participants.

4.1 Pilot Study Interviews

The interviews were conducted between August–September 2020. Since the COVID-19 pandemic made it challenging to conduct in-person or remote interviews with poultry farmers in SSA, we interviewed eight poultry farming researchers at Michigan State University who have conducted research in SSA (Malawi, Nigeria, and Tanzania). Three of them had PhDs, three had master's degrees, and two students pursuing advanced degrees. The interviews were held over Zoom and each lasted ~45 minutes. The interviews were semi-structured; our questions included: What tools or practices do farmers use to support their poultry farming activities? What factors do poultry farmers track when they are assessing the health of their poultry? What are your thoughts about automatically controlling these chicken coop conditions (temperature, humidity and lighting)?

The data from the interviews was analyzed using open coding and affinity diagramming. The patterns from open coding were used to generate categories that informed the themes of our findings.

4.2 Findings

Here, we present findings from our pilot interviews. These findings suggest that although poultry farmers in SSA already have strategies for controlling the conditions in their chicken coops, they do not have proper tools to help them anticipate when to apply these measures, particularly during adverse conditions. Below, we describe the particular challenges and opportunities that were raised by the poultry farming experts.

4.2.1 Control Measures for Heat Stress. Our participants consistently told us they were concerned about changing climatic conditions that negatively affect chicken production. The average temperature in SSA has been slowly rising over the past decades. This change has had a significant impact on agriculture and food systems in SSA [42, 47]. For poultry farming in particular, rising temperature and humidity can lead to an increased prevalence of heat stress in chickens [44]. High temperature that is accompanied by high humidity increases heat stress in chickens than high temperature with low humidity [35]. Our participants told us that this is because high humidity reduces loss of heat from chicken lungs thereby increasing heat stress. Heat stress disrupts the growth of chickens that are raised for human consumption because they do not eat as much when it is hot [27, 36]. Heat stress can also disrupt egg production by chickens that are raised for breeding. Temperature is not only important for coop environments, but also for the temperature of the water that the chickens drink. Like most other animals, chickens drink more water in warmer environments [7, 37]; at the same time, chickens will refuse to drink water that is above 30° C [5].

Poultry farmers in industrialized countries often use automated fans to cool their chicken coops. Poultry farmers in SSA, however, typically rely on manual alternatives, such as opening their coops' windows to increase air circulation or putting wet blankets in coops to absorb heat. Our participants emphasized that these alternatives are not common across all chicken coops. One expert who works with poultry farmers in Nigeria told us that planting trees around the coop, adding leaves under the coop's roof, and reducing the number of birds per coop are other strategies that farmers are encouraged to use. She said these measures are effective but costly in terms of time and money:

"This is an important one with changing climate conditions. Some farmers reported using blankets to keep their birds warm but since they don't usually live near the farms, they have to guess whether it will be needed or not. Other farmers have also relied on planting trees. Planting trees requires more time for the trees to grow. This cannot be easily implemented by poultry farmers. Additionally, reducing the number of birds per coop is mostly difficult because poultry farmers would need to have more than one coop. In most cases they can only afford one coop."

Our participants noted that although poultry farmers in SSA are aware of the importance of coop temperature and humidity, very few rely on sensors (e.g., thermometers) to continuously monitor these factors. Instead, they currently work on a fixed schedule or react to observations to manage their coops. Our experts confirmed that providing poultry farmers with a way to automatically be alerted when temperature conditions exceed optimal conditions would allow them to promptly respond to changes using strategies that are suited for their context.

4.2.2 Control Measures for Light. Participants frequently commented on the significance of proper lighting for inspecting chickens and maintaining the chickens' daily cycle. Poultry farmers will typically keep their coops lit during the day (9am–4pm) so that their chickens can eat. After 4pm, the lights in the coops are dimmed to encourage the chickens to rest. Chickens have different feeding requirements depending on their size, so it is important that the farmers regularly check the growth of their flock in order to adjust both their feed and sleep schedule.

Poultry farmers in the U.S. use poultry management systems (PMSs) that are programmed to automatically control the lighting conditions inside their chicken coops. Since PMSs are prohibitively expensive for a typical poultry farmer and require a high-voltage electricity supply, rural poultry farmers instead try to take advantage of sunlight to light their coops. Two ways that farmers do this is by constructing an open-air coop, or a coop with large windows. Our participants noted that improving access to sunlight often comes at the cost of decreased security, because thieves can easily breach coops with more openings. To take advantage of sunlight and keep their chickens safe, some farmers use two coops: an open-air coop to promote feeding during the day and a closed coop during the night to secure the chickens (however this option is expensive for most farmers). Beyond natural lighting, farmers manually turn on and off lamps to light their coops. As noted by one expert, farmers without access to electricity must rely on solar lamps, rather than electric lamps:

"One of the challenges of using artificial lighting to manage poultry feeding is electricity consumption. Most of farmers in rural areas do not have access to electricity so, it is important to consider other forms of electricity such as solar power."

We found that poultry farmers face challenges when working to effectively light their coops. They said this is a major challenge because poultry farmers do not precisely know how long they have had light/darkness in their chicken coops. Following this, participants suggested using existing technologies to provide chicken coop's lighting conditions to farmers.

4.2.3 Idiosyncratic Coop Configurations. Our findings suggest that poultry farmers in SSA use different strategies (e.g., opening windows and planting trees) to regulate environmental conditions that affect poultry farming. These strategies are not generalized across all poultry farmers: each poultry farmer might use a strategy that is different from another farmer. These findings suggest that every coop in this context is different: designing a fully automated system that controls chicken coop conditions might not work in some chicken coops.

Our participants also emphasized that electricity consumption should be taken into consideration when designing technology for poultry farms in SSA. Similar to what we found in literature [34, 46], participants told us that poultry farmers use various power sources (e.g., solar, batteries, national grid electricity and kerosene) for their chicken coops. These electricity sources are inconsistent and unreliable, which makes it difficult to take advantage of modern technologies. Further, they are affected by intermittent power failures and low input voltage which makes it difficult to use high voltage machines (e.g., electric fans). Our participants suggested designing a solar-powered system that would provide at-least enough power to periodically activate sensors to monitor chicken coops' conditions and to provide feedback to farmers. The different configurations in poultry farms informed our decision to design a sensor-based technology probe that captures temperature, humidity and lighting conditions then provide feedback to farmers. This feedback would prompt poultry farmers to use their traditional mechanisms to control chicken coop conditions.

5 DESIGNING NKHUKUPROBE

Commercially available sensor products often require Internet access and a smartphone app to retrieve data. This makes them inaccessible for most rural Malawian farmers. Just 16.4% of this population has Internet access, and only 7% own a smartphone [30, 34]. Instead, we used our formative research findings to inform the design of NkhukuProbe (Figure 1 and Figure 2) — a technology probe that captures room temperature, humidity, and light availability. Below, we describe the probe's features and how the probe was designed in Malawi for rural poultry farmers.

5.1 Constructing NKhukuProbe

The primary researcher is based in the U.S. and was unable to travel to Malawi due to COVID-19 related travel restrictions. We collaborated with local Malawians to ensure that NkhukuProbe met local aesthetic preferences and functional requirements. The local team included two research assistants: a computer science student from the University of Malawi, and an agriculture extension officer from the Farm Malawi. Three local technicians (an electrician, a carpenter, and a painter) were also a part of the team. Each technician

Figure 1: NkhukuProbe Hardware

was paid 43,000 MWK ($55 USD). The lead author and the local research assistants worked together to develop NkhukuProbe's software. The local technicians were responsible for procuring locally available materials to design and construct the probe's housing.

The housing is made of plywood since it is widely available in the area. We painted the housing brown to match the color of other furniture items in Malawian homes, which are also frequently made of wood. Holes were added to the housing to facilitate heat dissipation for the internal electronics. The local technicians soldered electronic components together, assembled the hardware, and tested the various components. Lastly, the research assistants and technicians tested NkhukuProbe using the local GSM and USSD network that would also be used by poultry farmers.

5.2 System Overview

NkhukuProbe has these primary components: the sensor hardware and a USSD mobile application. The main hub for the sensor hardware is an Arduino Uno micro-controller (5V operating voltage and 50mA direct current). The components connected to the microcontroller include a DHT11 temperature and humidity sensor, a photoresistor for measuring light, and a red light-emitting diode (LED) for communicating system status. The probe's control box is powered by a solar battery, that can last 30 hours with a full charge. Since 61% of the population own a basic mobile phone, we designed NkhukuProbe to access the Internet via the widely available Global System for Mobile Communications (GSM) network [30]; therefore, the hardware also includes a SIM900 GSM shield for transmitting data. The SIM card that accompanied each GSM shield was loaded with 4,000 MWK ($5 USD) worth of Internet data.

NkhukuProbe leverages the GSM network's USSD for communication; this protocol is supported by all feature phones. SMS notifications were also considered, but findings from our prior research suggest that rural farmers would find SMS notifications annoying [10]. By using USSD, the mobile app serves as an interface for farmers to monitor their coops' conditions whenever they see fit in real time. The app was developed using the AfricaIsTalking API[3], which supports USSD app development using PHP to connect to a MySQL server that hosts sensor data from the hardware.

6 PHASE II: NKHUKUPROBE DEPLOYMENT

In this section, we describe the context in which we deployed NkhukuProbe and the data collection methods we used to understand its perception by rural poultry farmers. We deployed NkhukuProbe in 15 Malawian households for one month (December 2020). The goal of our deployment was to field-test the probe, understand how participants could use sensors to control their chicken coop conditions, and inspire them to think of other ways of using sensors. Further, this was done to explore participants' perceptions of using sensors to support their poultry farming activities.

6.1 Study Context

According to Malawi's National Statistical Office (NSO), 84% of the population live in rural areas [34]. The study took place in Nsaru, a rural area located 30 miles from Malawi's capital, Lilongwe, in the central part of the country. We partnered with a local organization called "The Farm" to gain access to poultry farmers who can participate in the study. The Farm is a community-based organization that partners with smallholder farmers in Malawi. The organization's goal is to provide farmers with a livestock bundle that includes agricultural inputs (e.g., day-old chicks), training on livestock production and management, veterinary services and a competitive market for farmers to sell their produce. People living in this area practice a variety of income-generating activities: growing crops (e.g., maize, tobacco, and groundnuts), rearing animals (e.g., chickens, cattle, pigs, and goats), running small-scale businesses (e.g., selling groceries), and working in civil services (e.g., teachers and clinicians). Despite these income sources, poultry farming is considered an ordinary household activity. Comparable to the general population in Malawi, 80% of the residents of Nsaru have access to the local cellular network [30]. However, only 11.4% of the population are connected to national electricity grid; the rest of the population use solar (6.6%), battery (52%), paraffin (1.7%), candle (6.2%), firewood (4.4%), grass (2.1%), and other power sources (14.8%) [34].

6.2 Participants

Our research team worked closely with two agricultural extension officers associated with The Farm and the two local research assistants to identify participants, schedule appointments, and assist with in-person enrollment. We recruited participants using purposive sampling [6], selecting poultry farmers who had at least one mobile phone within their household. From the Farm's pool of 67 beneficiaries, we enrolled 15 households. During our deployment, we primarily interacted with the heads of each household shown in shown in Table 1

Participants lived in extended families that consisted of 3–12 members, and their coops held between 20–300 chickens. Those who had more than 150 chickens generally practiced poultry farming as a group; in other words, they collaborated with their neighbors to practice poultry farming. These groups have a chicken coop

[3] https://africastalking.com/ussd

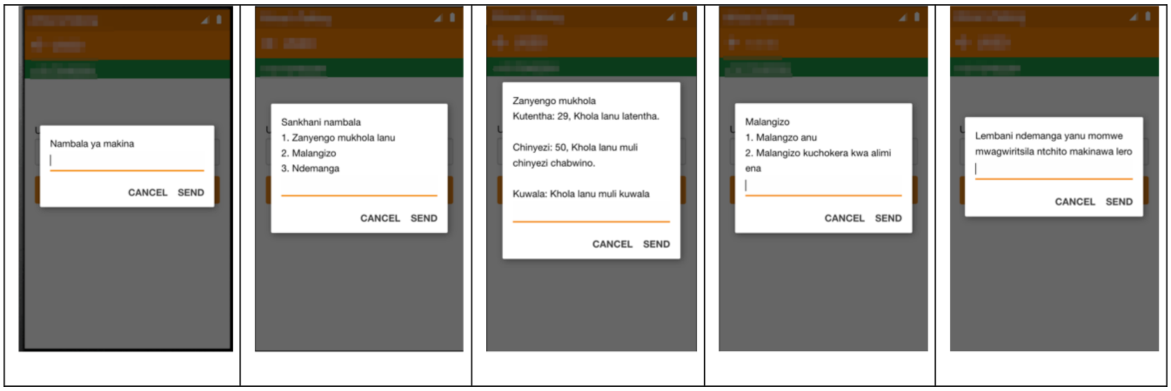

Figure 2: NkhukuProbe USSD user interface in Chichewa (Malawi's native language). A user enters device ID then continuously select a menu to view chicken coop conditions.

at one of the member's household. They share the responsibility of caring for the chickens. The poultry farmers were told that their participation was voluntary, and that all collected data would be anonymized.

6.3 Data Collection

We used in-depth interviews, observations, data logging, and diaries to collect data from participants. Our research assistants conducted the interviews in-person and were fluent in Chichewa and English—the languages commonly spoken in Nsaru. The interviews were digitally recorded for analysis.

The research assistants began by explaining the purpose of our research, and then asked participants for informed consent. The research assistants then conducted a semi-structured interview to understand the participant's existing poultry farming practices. Some of the questions included: What tools do you use to support your poultry farming activities? Tell us about your day-to-day activities to take care of your poultry. What do you know about sensor-based technologies?

The research assistants gave participants the NkhukuProbe and demonstrated how to use it. Participants then registered their phone number with their NkhukuProbe by submitting a device-specific ID through the USSD interface on the mobile app, after which they verified that they could check the device's temperature, humidity, and lighting data. Participants were also given printed instructions that explained NkhukuProbe's features; however, they were also told that they could use the probe for any activity. We also gave participants the research assistants' phone numbers; they were encouraged to call them if they encountered problems with the probe. Lastly, we provided participants with diaries to record their experiences. The diary included these prompts: Has anyone commented on the probe today? Did anything surprising happen with the probe today? What are your comments about the probe today?

We also sent participants weekly reminders (via SMS) to encourage them to write in the diaries. Participants were paid 2,000 MWK ($2.50 USD) for their time during the initial visit, and they were paid an additional 2,000 MWK every week to encourage them to write their experiences in the diary.

Table 1: Participants' demographic information

ID	Age	Gender	Household Size	# of Chickens
1	22	Male	8	120
2	38	Female	8	45
3	40	Male	6	80
4	33	Female	3	63
5	27	Female	10	32
6	22	Female	5	109
7	31	Male	5	69
8	36	Male	5	24
9	52	Female	8	180
10	21	Male	3	166
11	25	Male	6	148
12	40	Female	12	79
13	33	Female	4	23
14	54	Female	8	150
15	37	Male	6	56

After four weeks, the research assistants returned to participants' households and conducted follow-up interviews. The interview questions/prompts included: Tell me three things you appreciated about the system. Tell me three things you did not appreciate about the system. Walk me through an example of how you used the system. Are there any moments you expected the system to work, but it did not work?

After the interviews, participants were asked to give the research assistants a tour of their homes. During these tours, we asked them to show where and how they used NkhukuProbe. Following this phase of the study participants were given 2,000 MWK ($2.50 USD) as compensation. They were also allowed to keep the solar charger (used to power the probe). The research assistants toured participants' homes and observed the tools they used to take care of their poultry. They took photographs and fieldnotes to document their observations.

6.4 Data Analysis

Data analysis happened throughout the deployment period. The local research assistants shared their field notes with the rest of the team on a daily basis, and all the recorded interviews were transcribed. The notes were discussed during weekly meetings. We used open coding to identify recurring topics from the interviews, followed by affinity diagramming to organize these topics into themes. We used data triangulation to validate common themes from all of our data sources: interviews, diaries, photographs, data logging, and field notes. These data analysis methods were used to analyze data before and after the deployment of NkhukuProbe. Data logged on MySQL database tables was converted to CSV files. Then, we used Python to conduct exploratory data analysis.

7 FINDINGS

Here, we present our findings from before, and after the deployment of NkhukuProbe. Specifically, we describe the tools participants use to support their poultry farming activities. Next, we present findings after the deployment of NkhukuProbe focusing on how NkhukuProbe affected participants' practices and the other ways the farmers incorporated it into their everyday routine. Our findings suggest that participants found NkhukuProbe useful for monitoring their chicken coops' temperature, humidity and lighting conditions; identifying risk factors for poultry farming; and for thinking about other ways of using sensor-based applications in their homes.

7.1 Pre-NkhukuProbe Deployment

7.1.1 Participants' Poultry Farming Tools. Poultry farmers use various tools to support their activities. Our participants had many ways of controlling their coops' environment. Although the experts from our formative work were concerned about heat stress, the rural poultry farmers frequently mentioned needing to heat their coops in order to promote hatching and growth in younger chicks (less than six-weeks old). Ten participants told us that they use charcoal stoves to warm their coops (Figure 3, left), but such stoves come with their own challenges. Participants who had electricity access told us that they use 100 W lightbulbs installed near the bottom of the coops as an alternative heating source. These light bulbs are also used to provide lighting in chicken coops, especially at night. However, these farmers still relied on charcoal stoves, because lightbulbs are significantly more expensive than charcoal stoves; blackouts also make lightbulbs unreliable. Chickens can burn themselves if they interact with the stoves, which farmers prevent by covering their stoves with a wire mesh. Smoke that comes from the stoves can lead to the buildup of carbon monoxide. Four participants told us that they had previously lost chicks due to carbon monoxide suffocation:

> "There is a time when my daughter placed a charcoal stove while it was not well lit. I was at the market buying some groceries. When I returned home, I found smoke in the chicken coop. All the chicks I had at time died. The good thing is they were only ten of them and two weeks old. I learnt to keep the charcoal stove outside until it is well lit before taking it inside."

To avoid these issues, stove fires are ignited outside of the coop to allow for the initial smoke to dissipate. The coops also often had small windows to promote ventilation (Figure 3, right).

Participants remarked that they pay special attention to the temperature and humidity of their coops when the chickens are less than three months old since younger chicks are particularly sensitive to abnormal temperatures and humidity. Poultry farmers often check their coops at night to ensure that the charcoal stoves are still lit, and that the coops' temperature has not dropped too low:

> "It is very difficult to take care of chickens especially when they are less than six months old. I stay up at night to monitor the chicken coop's temperature. There is no specific way of telling whether it's too cold or warm. I just observe. If I find that it's cold, I light up my charcoal stove and wait with it outside to get well lit. Then I take it inside. I keep checking until morning."

Eleven participants told us they use buckets, water, and rugs to clean their chicken coops at-least once a day. Among these participants four told us that they clean two times a day to keep their chicken coops dry. These participants said that they went through a training program where they were taught that wet floors in chicken coops increase humidity beyond optimum conditions. Further, wet floors are a breeding ground for bacteria and parasites that might infect chickens. They were encouraged to consistently clean their chicken coops to remain dry.

Incubators are another important heating source for hatching eggs. Four participants in our study owned incubators, and they often shared their incubators as a service for other poultry farmers in the community. This serves as an income generating activity for incubator owners, who charge 100 MWK ($0.13 USD) per egg that is hatched. Since the poultry farmers do not own instruments for measuring temperature of their coops, they rely on their intuition to determine when and how to use their heating sources. Combined with the experts' concerns regarding heat stress due to climate change, our findings suggest that temperature and humidity tracking would enable a variety of quality-of-life improvements.

7.2 Post-NkhukuProbe Deployment

Over the course of four weeks, participants used their mobile phones to access data from their NkhukuProbe 1,072 times, this equates to an average of 34 server requests per day from all participants. This finding suggests that participants interacted with the probe every day. Logged data also suggests the server collected 29,101 data points (temperature, humidity and lighting logs) throughout the deployment period. We found that the poultry farmers did not only use their NkhukuProbes to check on the environmental conditions of their chicken coops, but also for other uses in and around their households.

7.2.1 Monitoring Temperature, Humidity and Lighting Conditions. All participants told us that they used NkhukuProbe to monitor the temperature, humidity and lighting conditions in their chicken coops. Nine participants said that they relied on the temperature information to determine when they needed to lower the temperature of their coop, while seven participants told us that they used

Figure 3: Examples of local poultry farming practices in Malawi: (left) a charcoal stove being warmed outside to later be placed at the center of the farmer's coop; (right) a coop with small windows to provide ventilation.

the temperature information to decide whether they needed to light a charcoal oven or not:

> "The sensor helped me to know the temperature conditions of my coop. When I see that it is too high, I was aware that I need to open the windows. When it's the temperature was low, I was also aware that it's time to light my charcoal stove and put it inside the coop."

By knowing when it was unnecessary to use a charcoal oven, participants noted that they were able to save money through efficient use of their charcoal supply. Poultry farmers also told us that knowing their coops' real-time chicken conditions encouraged them to clean their chicken coops often. They said that they used humidity as a signifier that their coop requires cleaning. Six participants used the humidity information from NkhukuProbe to determine when the floor of their coop was too wet. In response to those situations, the poultry farmers would either clean their chicken coops or open windows to provide ventilation (unless heat needed to remain inside the coop):

> "Sometimes the sensor was showing that there is high humidity in the coop. I have some basic knowledge and I know that humidity is associated with water vapor. I thought the floor of my chicken coop was wet too. So, that prompted me to clean my coop to keep it dry. That was helpful because after some time I could notice that the coop's humidity has reduced."

We also found that participants experimented with NkhukuProbe in their chicken coops. Despite the fact that research assistants verified that NkhukuProbe was functioning properly before leaving the poultry farmers' homes, participants still conducted their own experiments to convince themselves that it was working. These experiments were often based on the farmers' own observations or information that had been taught by extension officers. For example, one poultry farmer explained how they observed the arrangement of chickens in their coop to validate the temperature monitor:

> "The extension officers conducted a training where they told us that when it's hot, chickens are scattered, and when it's cold they are close together. I was using these things I already know to see whether the probe is working properly. I noticed that when the temperature is too high, the chickens were scattered around the whole coop only to come together when the temperature goes down."

Participants infrequently used light measurements from NkhukuProbe. Four participants remarked that the light data helped them realize that their coops were dark for a significant amount of time. This discovery was most common among poultry farmers whose chicken coops had small windows that could not be opened (Figure 4). Two of these participants—who had no electricity—said that the data from NkhukuProbe prompted them to let their chickens bask in the sun for a longer period of time. These findings suggest the urgency of providing information about chicken coop conditions to farmers so that they take necessary measures to maintain optimum conditions. Generally, participants found NkhukuProbe useful as it provides information about current chicken coop conditions.

7.2.2 Probing Poultry Farming Risk Factors. Data from the follow-up interviews and diaries suggest that participants used NkhukuProbe to learn about how temperature, humidity, and lighting conditions affected the health and about their chickens' egg productivity. This was particularly true among the poultry farmers who had gone through more formal education (at least secondary education, equivalent to grade 12 in the US education system). For example, one participant used NkhukuProbe to diagnose a sudden catastrophe within his flock:

> "What had happed was that quail had just hatched over a hundred chicks and I left them in a brooder. Later in the morning, I found that most of the chicks had died. So, I wondered what had happened. Last time I checked they were all okay. So, I used the sensor to check what had happened, so I realized that temperature was the problem. The temperature was so low. The heater wasn't really heating, and it was cold inside. So, if it wasn't for the sensor, I wouldn't

Figure 4: NkhukuProbe in one of our participants' chicken coop

> have known what had happened and I could have lost all of the chicks. I had put about 400 chicks in the brooder and about 270 died."

In cases when participants did not feel confident in interpreting the data for themselves, they turned to family members, friends, peers, and extension officers to help them interpret the data:

> "Previously they used to lay about 40 eggs per day but then there was a sudden drop in the numbers to about 18 eggs and other times about 12 so I was wondering why there was such a drop. My son, who is attending a business college, asked me to show him the diary where I was recording my experiences using the system. He checked temperature, humidity and lighting for each day and the number of eggs laid. He told me that it looks like during days we had high temperature; chickens laid few eggs. We called the extension officer and he advised us to replace the small windows with bigger one. We did this, and since that time, chickens are laying more eggs."

These findings demonstrate the various ways participants used the information provided by NkhukuProbe. This was influenced by the problems they are facing in their chicken coops. Further, this information appeared to encourage conversations between poultry farmers and agricultural extension officers. This suggests an opportunity to use the data as teaching material for poultry farmers.

7.2.3 Method of Notification. Participants commented on systems' notifications. Twelve participants told us that they would recommend using SMS notifications rather than USSD. These participants said that would help them receive notifications whenever chicken coop conditions are not within optimum limits.

> "I was thinking that the sensor should be able to send SMS notifications for any changes in temperature instead of using the USSD code every time you want to check the conditions. I am thinking of a time when there is an anomaly in the khola [chicken coop] but because you are not checking at that particular time, then the sensor wouldn't really be useful."

We implemented the probe using USSD for two reasons. First, USSD channel would allow participants to use the probe at no cost. Second, findings from our prior research suggest that SMS notifications become annoying whenever participants receive them when they are already aware of the situation [10]. Thus, we wanted to give more control to participants to check the conditions whenever they wanted to do so.

7.2.4 Automating Non-Digital Poultry Farming Equipment. Though participants found the information from the probe useful, they also thought about how it could be improved to better support their poultry farming activities. The probe allowed them to think beyond its capabilities: participants thought about how it could be improved to respond to their needs. We designed NkhukuProbe to monitor, rather than adapt to, the environmental conditions within chicken coops due to the poultry farmers' limited resources (e.g., electricity, hardware) and the diversity of their coops' designs. Nevertheless, ten participants told us that they wished that their NkhukuProbe could modify the configuration of the coop on their behalf. In fact, three participants told us that their neighbors asked them if NkhukuProbe had such functionality:

> "My neighbors asked me what the system was. So, I explained that is used to monitor temperature, light and humidity in my khola [chicken coop]. They asked me whether the sensor is able to self-adjust conditions whenever there are changes in temperature. I felt that it would really be useful if it could control things by itself."

Requiring additional equipment, such as fans and servomotors, would introduce additional points of failure and impose long-term costs on poultry farmers due to maintenance requirements. Prior work has encouraged researchers to develop technology that supports existing practices within users' own contexts [8, 15]. In the case of rural poultry farming, these existing practices involve non-digital equipment like charcoal stoves and windows. Building on this prior research, our discussion proposes ways of integrating non-digital equipment with sensors.

7.2.5 Probing Non-Poultry Farming Activities. Data from the diaries suggest that NkhukuProbe was not only used in chicken coops, but also within farmers' homes (Figure 5). Seven participants told us that they used NkhukuProbe to monitor the temperature and humidity conditions in their bedrooms. For example, one participant noted:

> "I was just interested to use the sensor in my main house. I took it to my bedroom and check temperature conditions. It just gave me a sense of how hot the room is. That helped me open the windows when it's daytime but at night, I cannot open the windows. If I had electricity connection, I would have bought an

Figure 5: NkhukuProbe in one of our participants' household

> electric fan to use at night. . .I think there is more a sensor could do. For example, I wish there was also a way to know whether there is fresh air in my bedroom."

Another participant—who used NkhukuProbe in their bedroom—noticed that the humidity would rise in the morning. After investigating the structural integrity of the wall and roof, he noticed that there were small holes along the edges that were causing humid air to enter his home. Although NkhukuProbe did not help him to solve the problem, it was helpful to identify areas that required maintenance within his household. Participants speculated about other potential uses for sensors in their homes. Many of the speculations were related to air quality. NkhukuProbe's open-ended design allowed participants to speculate on other ways sensors can be used to support domestic life. These speculations led to an understanding of potential areas of using sensors in Malawian homes. These findings suggest that participants are interested to use sensors to improve air quality in this context.

8 DISCUSSION

Returning to our research questions, we offer evidence to suggest that sensor-based technologies can support poultry farming activities in Malawi. While prior research suggests that sensors can automate digital equipment [39, 40], it is unclear how they can support poultry farming practices. Our study's findings suggest the potential for using sensors to support poultry farming activities in this context. Participants' interactions with NkhukuProbe generated detailed findings about their daily activities. Further, NkhukuProbe inspired participants to imagine novel ways to use sensor-based technologies in their homes. Our discussion focuses on implications for designing sensor-based technologies to support poultry farming activities in SSA. We also discuss future opportunities for designing sensor-based technologies to support activities in Malawi's domestic space. This section provides a discussion on the potential of sensor-based technologies in reducing time and resources for poultry farming activities, improving poultry farmers' existing tools, and other applications of sensor-based technologies.

8.1 Saving Time and Resources

Our findings suggest that NkhukuProbe supported participants' efforts to keep their chicken coops within optimum conditions. Participants' interactions with NkhukuProbe allowed them to track environmental conditions in their chicken coops without visiting the coops. The probe allowed participants to save time and focus on other household activities (e.g., participants who stayed awake in their chicken coops to keep monitoring temperature conditions). This finding suggests that sensor-based technologies can help reduce the amount of time poultry farmers spend monitoring their chicken coops' temperature conditions.

Participants' experience using NkhukuProbe also suggest that sensor-based technologies have the potential to save resources (e.g., energy). NkhukuProbe provide real-time temperature, humidity and lighting conditions for participants' chicken coops. This allowed them to know the proper time to switch on/off lights (those who had electricity), clean their coops to reduce humidity as well as lit their charcoal burners to keep chicken coops warm. Thus, participants were able to use their tools only when it was necessary. Prior research suggests that the use of charcoal has negative impacts on the environment [8, 18]. Thus, the utilization of sensor-based technologies can potentially minimize unnecessary use of resources that endanger the environment. These insights provide opportunities that draw attention to new ways to use sensors; that is ways that have not been traditionally considered in HCI. Within HCI, sensors have been used to improve people's domestic activities in various ways including sensing solutions for: health, domestic security, locating missing objects, utility monitoring and specialized activities in the kitchen [10, 11, 22, 25, 26, 38]. Our findings extend this literature by demonstrating the potential of using sensors to sustainably save the environment when people in SSA are provided with information that helps to minimize the use of resources (e.g., charcoal) that endanger the environment.

8.2 Monitoring Non-Digital Tools

Our findings also suggest that a majority of tools used for poultry farming in Malawi are non-digital technologies (e.g., charcoal stove, feeding basins, and manual windows). Participants wanted to automate their poultry farming activities (e.g., heating coops). HCI researchers have emphasized the importance of not using technology as a tool to replace people's existing practices [48, 50]. In order to maintain this standard within the Malawian domestic space, researchers and designers should seek ways to augment existing non-digital technologies with sensor-based technologies.

Prior HCI research proposes a shift from designing sensing technologies to designing ubiquitous systems that incorporate traditional tools along with digital devices [24]. Similarly, we propose augmenting existing poultry farming non-digital tools with sensor-based technologies. One way this could be done is by leveraging "methodical assemblages"; that is designing technologies by identifying categories and order where particular things routinely combine to open up new opportunities for technological applications [12]. Domestic life has a local order that organize activities in the home. For example, we learned that poultry farmers first put charcoal stove outside, add charcoal, lit it then wait for it until it is well lit. Once it is lit, they take it inside their chicken coop. They regularly monitor their coops to see whether they should add more charcoal. When they add charcoal, they take it outside again and wait until it is well lit. This is a normal routine, that farmers follow to keep their coops warm. We also learned that participants regarded this routine as time consuming. Therefore, we suggest finding better ways of tracking charcoal stoves' status during this process. For example, charcoal stoves could be augmented with sensors that track their status—whether they are well lit, the temperature is low, or they are producing carbon monoxide. This would reduce the amount time poultry farmers monitor stoves. Further, it would ensure that poultry farmers take charcoal stoves inside coops when they are free of carbon monoxide.

8.3 Probing with NkhukuProbe

A goal of our study was to explore different ways participants could use NkhukuProbe to support their daily activities. According to Hutchinson *et al.*, one of the goals of a technology probe is to inspire users to think of other ways of using technologies in their context [19]. We found different ways participants used NkhukuProbe during our deployment.

NkhukuProbe was a successful technology probe, because it inspired participant to contextualize its features. Participants experimented with the probe (with their neighbors) as well as use it to inspect their chicken coops. The open-ended nature of NkhukuProbe allowed participants to use it where they saw fit—we did not restrict participants to only use the probe for poultry farming activities. The probe prompted inspirational stories that are important for designing sensor-based technologies for this context. Participants who used NkhukuProbe in their households imagined using sensors to monitor their homes' air quality. Though numerous researchers have explored the application of sensors to improve air quality [32, 41], these studies have mostly taken place in industrialized countries. While researchers have started exploring this area in developing countries (e.g., [15]), most solutions are proposed at a regional scale. Our study provides evidence to extend this domain of research at household level where users have more control of their equipment.

Our findings also suggest that data provided by NkhukuProbe was used as teaching material for poultry farmers. Poultry farmers who had little knowledge about poultry farming contacted other family members, neighbors and extension officers to seek advice. NkhukuProbe's data encouraged poultry farmers to engage in conversations with agricultural extension officers to learn more about poultry. Prior research suggests that poultry farmers do not have substantial access to agricultural extension officers [4, 28, 45]. Further, rural areas are resource constrained; that is, they tend to have poor road networks, low literate populations, limited electricity connection, and insufficient social services (veterinary services for their domestic animals). These factors make it difficult for extension officers to reach rural areas. Our study demonstrates the possibility of using data from sensor-based technologies to increase interaction between poultry farmers and agricultural extension officers.

8.3.1 Other Applications of Sensors in Malawi's Poultry Industry. NkhukuProbe prompted participants to consider how sensors can be used in the poultry farming industry. Before deployment, nine participants said they had no knowledge of technology in this space, while six mentioned incubators, heaters, and light bulbs as familiar technologies; nobody mentioned thermometers, electric fans, or feeding systems. Despite their lack of awareness of sensor-based technologies, participants seemed excited by their potential and provided suggestions on how sensors could be used. Seven participants had lost chickens to burglars or predators (e.g., dogs and cats), so many poultry farmers were interested in a camera-based security system to monitor their coops. This coincides with prior findings in Kenya where participants repurposed a motion detection system for both domestic security and poultry monitoring [10].

Poultry farmers also expressed interest in using sensors to diagnose diseases in their chickens. They told us that they rely on extension officers to visit them and diagnose chickens; however, the officers' services are often insufficient because they infrequently visit the area. Participants believed that sensor-based technologies could be used to detect abnormal sounds produced by their chickens (e.g., coughs). Knowing the type and frequency of sound chickens produce would be enough information to either alert the farmer that there is an issue with their flock. Ultimately, this information could be forwarded to an extension officer so that they can prioritize visiting that farmer sooner.

9 LIMITATIONS AND FUTURE WORK

Our study provides some evidence that poultry farmers in SSA want to integrate sensor-based technologies with the existing tools they use for poultry farming. However, our study was not without limitations. We acknowledge that, due to COVID-19 pandemic and infrastructural challenges (hardware infrastructure and internet access for poultry farmers), it was difficult to directly interact with poultry farmers during the study's formative phase. Further, the four-week period was not sufficient to fully learn about the long-term implications of NkhukuProbe in Malawian households; clearly more research is required. Participants also suggested different ways of improving NkhukuProbe. We plan to use this study's findings to develop higher-fidelity prototypes that will be deployed in Malawian households for an extended period to understand long-term implications of sensor-based technologies for poultry farming in Malawi.

10 CONCLUSION

In this paper, we explored the role of sensor-based technologies in supporting poultry farming in Malawi. Our findings suggest different ways poultry farmers used NkhukuProbe to support their activities (e.g., coop inspection, saving resources and time). These findings deepen the HCI community's understanding of using sensor-based technologies to support poultry farming activities. Our study suggests the potential of using sensor-based technologies to save time, resources, and the environment. Further, the use of NkhukuProbe in Malawi opened new opportunities for studying sensor-based technologies in the sub-Saharan Africa. Our discussion provides design implications for designing poultry farming management system in this context.

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