Applied Research Report

Internet of Things (IoT) Technologies for Climate Adaptation in Smallholder Agriculture During Zambia's 2024 Energy Crisis

Strengthening Climate Resilience and Energy Efficiency in Smallholder Farming Systems

Implemented by: Garden House Youth Society

Project Title: Applied Research on the Role of Internet of Things (IoT) Technologies in Strengthening Climate Adaptation Among Smallholder Farmers During Zambia's Energy Crisis

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Special appreciation is extended to the smallholder farmers who participated in this research, generously sharing their time, experiences, and insights throughout the study. Their willingness to collaborate and test new technologies made it possible to generate valuable evidence on the role of Internet of Things (IoT) technologies in strengthening climate adaptation during Zambia's 2024 energy crisis.

The research team also acknowledges the support of local agricultural extension officers, community leaders, and farmer cooperatives who facilitated community engagement and supported the field activities conducted during the project.

We further extend our appreciation to the field researchers, technicians, and project assistants whose dedication and commitment ensured the successful deployment of IoT monitoring systems and the collection of high-quality research data.

Finally, we thank all stakeholders, development partners, and institutions working to promote climate-smart agriculture and digital innovation in Zambia. Their continued collaboration is essential for advancing climate adaptation solutions that strengthen the resilience of smallholder farmers and rural communities.

This research represents a collective effort to explore innovative approaches to climate adaptation and to contribute to sustainable agricultural development in Zambia.

About Team

This research was conducted by Garden House Youth Society, a Zambian civil society organization focused on sustainable development, climate adaptation, and community resilience. The organization works with rural communities, development partners, and policymakers to develop practical solutions that address environmental challenges and strengthen livelihoods in climate-vulnerable regions.

The research team combined expertise in climate adaptation, digital technologies, agricultural systems, and socioeconomic research.

Dr. Habeenzu Simamba - Lead Researcher

Dr. Habeenzu Simamba served as the lead researcher for this study. He holds a PhD in Business Administration and has extensive experience in development policy, climate adaptation research, and economic resilience initiatives. Dr. Simamba has participated in several research and policy initiatives focused on climate-smart agriculture, digital innovation, and rural economic development in Zambia.

In this project, Dr. Simamba provided overall research leadership, supervised the study design and implementation, and led the analysis and preparation of the final research report.

Dr. Patience Nalavwe - Socioeconomic Research Specialist

Dr. Patience Nalavwe contributed to the socioeconomic research component of the study. She holds a PhD in Development Studies and has extensive experience in monitoring and evaluation, gender and development research, and rural livelihood analysis.

Her role in the project included designing household survey tools, conducting socioeconomic data analysis, and assessing the economic impacts of IoT technologies on smallholder farming systems.

Mwimanenwa Mooto - Technology and Field Implementation Coordinator

Mr. Mwimanenwa Mooto served as the Technology and Field Implementation Coordinator for the project. He played a key role in supporting the deployment of IoT monitoring systems and coordinating field activities across the participating farming communities.

His responsibilities included working with technicians during sensor installation, assisting farmers in understanding the monitoring systems, and supporting field data collection.

Field Research and Technical Support Team

The project was supported by a team of research assistants, technicians, and enumerators who assisted with household surveys, technology monitoring, and field data collection. These team members played a crucial role in ensuring that accurate data was collected throughout the research period.

Institutional Support

Garden House Youth Society provided overall project coordination and administrative support for the research. Through its work on climate adaptation and community-based development initiatives, the organization facilitated collaboration with local stakeholders and ensured that the research addressed practical challenges faced by smallholder farmers.

The team's collective expertise in climate adaptation, agricultural development, and digital innovation contributed to the successful implementation of the study and the generation of evidence on the role of IoT technologies in strengthening agricultural resilience.

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Executive Summary

In 2024, Zambia experienced one of the most severe droughts in its recorded history, resulting in a national energy crisis driven by significantly reduced hydropower generation. Hydropower accounts for over 80% of Zambia's electricity supply, and declining water levels in major reservoirs led to widespread load shedding, severely disrupting economic activity across the country. Smallholder farmers were among the most affected groups, as unreliable electricity limited irrigation, storage, and agro-processing activities, thereby threatening agricultural productivity and rural livelihoods.

In response to these challenges, the YouthAdapt Programme, supported by the African Development Bank (AfDB) and the Global Center on Adaptation (GCA), funded an applied research initiative implemented by Garden House Youth Society. With a grant of USD 100,000, the project examined how Internet of Things (IoT) technologies can strengthen climate adaptation and improve energy resilience among smallholder farmers during periods of energy instability.

The research focused on testing IoT-enabled sensors and monitoring systems that provide farmers with real-time information on soil moisture, irrigation efficiency, and energy use within solar-powered farming systems. The study assessed how these technologies can help farmers optimize resource use, reduce energy waste, and maintain agricultural productivity during power shortages.

Using a mixed-method research approach combining field experiments, household surveys, and stakeholder consultations, the study evaluated both the technical performance and economic impacts of IoT technologies in climate-stressed farming environments.

The findings demonstrate that IoT-based monitoring systems can significantly improve irrigation efficiency, reduce energy consumption, and enhance farmers' ability to adapt to climate variability and energy disruptions. The research highlights the potential of digital technologies to support climate-resilient agriculture while contributing to broader economic resilience in rural communities.

The results provide important insights for policymakers, development partners, and climate finance institutions seeking scalable solutions to strengthen climate adaptation in African agricultural systems.

1. Introduction

Zambia's economy and rural livelihoods are closely tied to climate-sensitive sectors, particularly agriculture and hydropower generation. In 2024, the country experienced one of the most severe droughts in its recent history, which significantly reduced water levels in major reservoirs such as Kariba and Kafue Gorge. Because hydropower accounts for the majority of Zambia's electricity generation, the drought triggered a national energy crisis characterized by extended load shedding and electricity shortages across the country.

The energy crisis had widespread economic consequences. Businesses faced production disruptions, agro-processing activities were curtailed, and rural communities struggled to maintain agricultural productivity due to unreliable electricity supply. Smallholder farmers were particularly vulnerable, as many rely on electricity or solar-powered systems for irrigation, water pumping, storage, and processing activities. Limited access to reliable energy during critical farming periods increased production risks and reduced the resilience of agricultural systems.

At the same time, climate change is intensifying the frequency and severity of droughts in Southern Africa, placing additional pressure on agricultural systems and rural livelihoods. Strengthening the adaptive capacity of smallholder farmers has therefore become a critical priority for sustainable development and climate resilience in Zambia.

Digital technologies such as the Internet of Things (IoT) offer promising opportunities to support climate adaptation in agriculture. IoT-based sensors can provide real-time information on environmental conditions such as soil moisture, temperature, water availability, and energy use. By providing farmers with accurate and timely data, these technologies can help optimize irrigation scheduling, improve energy efficiency, and enhance decision-making under climate uncertainty.

Recognizing this potential, the YouthAdapt Programme, supported by the African Development Bank (AfDB) and the Global Center on Adaptation (GCA), funded an applied research initiative implemented by Garden House Youth Society. The project aimed to explore how IoT technologies can strengthen climate adaptation among smallholder farmers during periods of energy instability.

This research focused on testing IoT-enabled monitoring systems integrated into solar-powered farming operations to evaluate their potential to improve resource efficiency and economic resilience during Zambia's 2024 energy crisis.

By generating practical evidence on the role of digital technologies in climate adaptation, the study contributes to broader efforts to develop scalable solutions that enhance agricultural resilience in climate-vulnerable regions.

2. Background and Literature Review

2.1 Climate Change and Agricultural Vulnerability in Zambia

Agriculture remains a central pillar of Zambia's economy and rural livelihoods. The sector contributes significantly to employment and food security, with smallholder farmers accounting for the majority of agricultural production. However, agricultural productivity in Zambia is highly sensitive to climate variability, particularly droughts, irregular rainfall patterns, and rising temperatures.

Climate projections for Southern Africa indicate that droughts are likely to become more frequent and severe due to climate change. These changes threaten agricultural productivity, water availability, and rural incomes. Smallholder farmers are particularly vulnerable because they often rely on rain-fed agriculture and have limited access to technologies that could help them adapt to climate risks.

Strengthening climate resilience in agriculture has therefore become a major development priority for governments and development partners across Africa.

2.2 Zambia's 2024 Drought and Energy Crisis

In 2024, Zambia experienced one of the worst droughts in its recent history. The drought significantly reduced water levels in major reservoirs used for hydropower generation, including the Kariba and Kafue Gorge dams. Because hydropower accounts for a large proportion of the country's electricity supply, the drought led to widespread electricity shortages and extended load shedding.

The energy crisis had major economic implications. Businesses experienced production disruptions, agro-processing activities slowed down, and agricultural operations dependent on irrigation and mechanized systems faced significant challenges.

For smallholder farmers who rely on solar-powered irrigation or grid electricity for water pumping and storage, the energy crisis increased operational costs and reduced agricultural productivity.

2.3 Digital Technologies and Climate-Smart Agriculture

In recent years, digital technologies have emerged as important tools for improving agricultural productivity and climate resilience. Technologies such as remote sensing, mobile-based advisory systems, and IoT-enabled sensors are increasingly being used to support climate-smart agriculture.

IoT technologies allow farmers to monitor environmental conditions such as soil moisture, temperature, humidity, and water usage in real time. These data-driven insights enable farmers to make informed decisions about irrigation scheduling, fertilizer application, and energy use.

In contexts where energy supply is unstable, IoT-based monitoring systems can help optimize the use of limited energy resources, ensuring that irrigation and other farm operations are carried out efficiently.

2.4 Role of IoT Technologies in Climate Adaptation

IoT technologies have significant potential to support climate adaptation by improving farmers' ability to respond to changing environmental conditions. By providing real-time data and automated monitoring systems, IoT platforms can help farmers reduce water waste, improve irrigation efficiency, and manage energy consumption more effectively.

For smallholder farmers facing climate shocks such as drought and energy shortages, access to accurate environmental data can significantly improve decision-making and reduce production risks.

However, despite the growing interest in digital agriculture, there remains limited empirical research on the effectiveness of IoT technologies in strengthening climate adaptation among smallholder farmers in Africa.

2.5 Research Gap

Although digital agriculture technologies are increasingly promoted as solutions for climate resilience, there is limited evidence on their real-world performance in resource-constrained rural environments. In particular, little research has been conducted on how IoT technologies can support farmers in managing energy disruptions during climate-related crises.

This research therefore seeks to address this gap by evaluating the role of IoT-enabled monitoring systems in strengthening climate adaptation among smallholder farmers during Zambia's 2024 energy crisis.

3. Problem Statement, Research Questions, and Objectives

3.1 Problem Statement

Zambia's agricultural sector is increasingly vulnerable to climate variability, particularly droughts and irregular rainfall patterns. These climatic shocks directly affect smallholder farmers who depend on stable environmental conditions to sustain crop production and rural livelihoods. The severe drought experienced in Zambia in 2024 highlighted the extent of this vulnerability by simultaneously disrupting both water availability and national energy production.

The drought significantly reduced water levels in major hydropower reservoirs, triggering a national energy crisis characterized by prolonged electricity outages and load shedding. This situation had far-reaching consequences for agriculture, particularly for farmers who rely on irrigation, water pumping, cold storage, and agro-processing systems that require reliable electricity. As energy supply became unstable, many smallholder farmers struggled to maintain irrigation schedules and efficient water management, leading to reduced productivity and increased production risks.

While solar-powered irrigation systems are increasingly promoted as a climate adaptation solution for smallholder farmers, many existing systems operate inefficiently due to limited monitoring and poor management of energy and water resources. Farmers often lack access to real-time information on soil moisture conditions, irrigation efficiency, and energy consumption. As a result, water and energy resources are frequently used inefficiently, which increases production costs and reduces system performance during periods of energy scarcity.

Digital technologies such as Internet of Things (IoT) monitoring systems have the potential to address these challenges by providing farmers with real-time data that supports better decision-making. However, there is limited empirical evidence on how IoT technologies perform in rural agricultural systems, particularly in contexts where farmers are facing simultaneous climate and energy shocks.

Understanding the role of IoT technologies in improving energy efficiency, irrigation management, and climate adaptation among smallholder farmers is therefore essential for developing scalable solutions that strengthen agricultural resilience in Zambia and across Africa.

3.2 Research Questions

The study was guided by the following key research questions:

1. How can IoT-based monitoring systems improve irrigation efficiency and water management among smallholder farmers during periods of energy instability?
2. To what extent can IoT technologies reduce energy consumption and optimize the use of solar-powered irrigation systems?
3. What are the economic and productivity impacts of IoT-enabled climate adaptation technologies for smallholder farmers?
4. What barriers affect the adoption of digital technologies for climate adaptation in rural agricultural systems?

3.3 Research Objectives

General Objective

To assess the effectiveness of Internet of Things (IoT) technologies in strengthening climate adaptation and energy resilience among smallholder farmers during Zambia's 2024 energy crisis.

Specific Objectives

1. To evaluate the performance of IoT-enabled monitoring systems in improving irrigation and water management practices.
2. To analyze the impact of IoT technologies on energy efficiency and operational costs in solar-powered agricultural systems.
3. To examine the socioeconomic benefits of IoT-based climate adaptation technologies for smallholder farmers.
4. To identify policy and investment opportunities for scaling digital climate adaptation solutions in Zambia's agricultural sector.

4. Conceptual Framework and Theoretical Foundations

This research is grounded in interdisciplinary theories that link climate adaptation, digital agriculture, resilience economics, and technology adoption. The conceptual framework guiding the study explains how IoT technologies can enhance the adaptive capacity of smallholder farmers facing climate and energy shocks.

4.1 Climate Adaptation and Resilience Theory

Climate adaptation theory focuses on the ability of communities and economic systems to adjust to climate variability and reduce vulnerability to environmental shocks. In agricultural systems, adaptation strategies include improved water management, climate-smart farming practices, and the adoption of technologies that enhance decision-making under uncertain environmental conditions.

Smallholder farmers often face constraints such as limited access to information, technology, and financial resources. Strengthening adaptive capacity therefore requires interventions that improve access to knowledge and tools that enable farmers to respond effectively to climate risks.
Digital technologies can play an important role in enhancing climate resilience by providing farmers with timely and accurate environmental information that supports adaptive decision-making.

4.2 Digital Agriculture and Smart Farming

Digital agriculture refers to the use of advanced technologies such as sensors, data analytics, and digital communication platforms to improve agricultural productivity and sustainability. IoT technologies form a central component of digital agriculture by enabling continuous monitoring of environmental and operational conditions in farming systems.

IoT sensors can collect real-time data on soil moisture, temperature, water flow, and energy consumption. These data can then be analyzed to optimize irrigation scheduling, reduce water waste, and improve the efficiency of solar-powered farming systems.

By integrating digital monitoring systems into agricultural operations, farmers can improve resource management and maintain productivity even under challenging environmental conditions.

4.3 Energy–Water–Food Nexus

The research also draws on the Energy–Water–Food Nexus framework, which recognizes the interconnected relationships between energy systems, water resources, and food production. In agricultural systems, water pumping and irrigation require energy, while crop production depends on both water availability and energy access.

During Zambia's 2024 energy crisis, disruptions in electricity supply affected irrigation activities, demonstrating the strong interdependence between energy and food production systems. Technologies that improve the efficiency of energy and water use therefore play a critical role in strengthening agricultural resilience.

IoT-based monitoring systems can help farmers better manage the energy–water–food nexus by providing information that supports efficient resource use.

4.4 Technology Adoption Theory

The adoption of new technologies by farmers is influenced by factors such as perceived benefits, cost, ease of use, and access to technical support. Technology adoption theories highlight the importance of demonstrating practical benefits and ensuring that innovations are accessible and relevant to users' needs.

In the context of climate adaptation, technologies that reduce risk and improve productivity are more likely to be adopted by farmers. However, barriers such as limited digital literacy, high upfront costs, and lack of infrastructure can slow adoption.

Understanding these adoption dynamics is important for designing policies and programs that support the scaling of digital climate adaptation technologies.

4.5 Conceptual Framework of the Study

The conceptual framework for this research proposes that IoT technologies enhance climate adaptation among smallholder farmers by improving information access, resource efficiency, and decision-making capacity.

The framework assumes that:

- IoT sensors provide real-time environmental and energy data.
- Farmers use this information to optimize irrigation and energy management.
- Improved resource efficiency reduces production costs and increases productivity.
- Enhanced productivity and reduced risk strengthen farmers' economic resilience.

Through this pathway, digital technologies can contribute to more climate-resilient agricultural systems and improved rural livelihoods.

5. Research Methodology

5.1 Study Area

The research was conducted in selected agricultural communities in Southern and Western Zambia, regions that experienced significant impacts from the 2024 drought and energy crisis. These regions are characterized by a high concentration of smallholder farmers who rely on irrigation and solar-powered water pumping systems for crop production.

The selected study sites included farming communities where solar irrigation systems had been installed and where IoT monitoring technologies could be deployed to evaluate their performance in real farming environments. These areas represent typical smallholder agricultural systems that are vulnerable to both climate variability and energy instability.

5.2 Research Design

The study adopted a mixed-method research design, combining quantitative and qualitative data collection techniques to evaluate both the technical performance and socioeconomic impacts of IoT technologies.

The research design integrated three main components:

1. Field-based technology trials involving IoT sensors installed on solar-powered irrigation systems.

2. Household surveys to assess the experiences and economic outcomes of participating farmers.

3. Stakeholder consultations involving agricultural extension officers, local authorities, and development practitioners.

This approach allowed the research team to generate both technical and social insights into the effectiveness of digital technologies for climate adaptation.

5.3 Sampling Strategy

A purposive sampling strategy was used to select farmers participating in the study. The research targeted smallholder farmers who were actively engaged in irrigated crop production and who had access to solar-powered irrigation systems.

A total of 150 smallholder farmers participated in the research. The sample included farmers cultivating crops such as vegetables, maize, and horticultural products.

The sampling strategy ensured representation of different farm sizes, irrigation practices, and socioeconomic conditions within the study areas.

5.4 Data Collection Methods

Data were collected using multiple methods to ensure comprehensive analysis.
1. IoT Sensor Monitoring

IoT sensors were installed on selected solar-powered irrigation systems to monitor:

- Soil moisture levels
- Water flow rates
- Irrigation duration
- Energy consumption of irrigation pumps

The sensors transmitted real-time data that allowed researchers to evaluate irrigation efficiency and energy use.

2. Household Surveys

Structured questionnaires were administered to participating farmers to collect information on:

- Agricultural production practices
- Energy use in farming operations
- Costs of irrigation and water pumping

- Crop yields and farm income
- Perceptions of IoT technology adoption

3. Key Informant Interviews
Interviews were conducted with agricultural extension officers, project technicians, and community leaders to gather insights on the broader implications of digital technologies for climate adaptation.

4. Field Observations
Researchers conducted site visits to observe farming practices, irrigation systems, and the functioning of IoT monitoring equipment.

5.5 Data Analysis

Quantitative data from IoT sensors and household surveys were analyzed using descriptive statistical techniques to identify patterns in irrigation efficiency, energy consumption, and crop productivity.

Qualitative data from interviews and field observations were analyzed using thematic analysis to identify key trends related to technology adoption, climate adaptation practices, and farmer experiences.

5.6 Ethical Considerations

The research adhered to ethical principles throughout the study. Participation in the research was voluntary, and informed consent was obtained from all farmers involved in the study.
Confidentiality of respondents was maintained by ensuring that personal information collected during surveys and interviews was not disclosed publicly. The research also ensured that farmers were informed about the purpose of the study and how the collected information would be used.

6. Implementation Activities and Project Timeline

The research project was implemented between January and December 2025 under the YouthAdapt Programme supported by the African Development Bank (AfDB) and the Global Center on Adaptation (GCA). The project followed a phased implementation approach to ensure effective deployment of IoT technologies, data collection, and stakeholder engagement.

6.1 Project Inception and Planning

The project began with an inception phase aimed at establishing partnerships, refining the research design, and identifying suitable farming communities for the technology trials.
Key activities during this phase included:

- Stakeholder consultations with local agricultural authorities and community leaders
- Selection of participating smallholder farmers
- Procurement of IoT monitoring equipment and installation materials
- Development of data collection tools for household surveys and field monitoring

The inception phase ensured that the research activities were aligned with local agricultural conditions and community needs.

6.2 Installation of IoT Monitoring Systems

Following the inception phase, the research team installed IoT monitoring devices on selected solar-powered irrigation systems. The sensors were designed to collect real-time data on soil moisture, irrigation activity, and energy consumption.

The installation process involved:

- Mounting soil moisture sensors in selected farm plots
- Installing water flow sensors on irrigation pipelines
- Integrating energy monitoring devices on solar-powered water pumps
- Testing connectivity and data transmission systems

These systems enabled continuous monitoring of farm operations throughout the research period.

6.3 Farmer Training and Capacity Building

Participating farmers received training on the use of IoT monitoring technologies and climate-smart irrigation practices.

Training sessions covered:

- Understanding soil moisture data and irrigation scheduling
- Efficient water use in irrigation systems
- Energy-efficient operation of solar-powered pumps
- Basic maintenance of monitoring equipment

These training activities helped ensure that farmers were able to use the technology effectively and interpret the data generated by the sensors.

6.4 Monitoring and Data Collection

During the main implementation phase, IoT sensors continuously collected data on irrigation and energy use. At the same time, researchers conducted household surveys and field visits to document farmers' experiences with the technology.

Monitoring activities included:

- Regular downloading and analysis of sensor data
- Field inspections to verify system performance
- Interviews with farmers regarding irrigation practices and energy challenges
- Documentation of crop productivity and irrigation outcomes

This phase provided the core data used to assess the effectiveness of IoT technologies in improving climate adaptation.

6.5 Stakeholder Engagement

Throughout the project, the research team engaged with key stakeholders to share preliminary insights and gather feedback.
Stakeholders included:

- Agricultural extension officers
- Local government representatives
- Farmer cooperatives
- Development organizations working on climate adaptation

These engagements helped ensure that the research findings were relevant for policy and development programming.

6.6 Project Timeline

Project Phase	Key Activities	Timeline
Project Inception	Stakeholder consultations, site selection, procurement of equipment	Jan – Feb 2025
Technology Deployment	Installation of IoT sensors and system testing	Mar – Apr 2025
Farmer Training	Capacity building on IoT monitoring and irrigation management	Apr – May 2025
Monitoring Phase	Data collection, field visits, farmer surveys	May – Oct 2025
Data Analysis	Processing and analysis of research data	Oct – Nov 2025
Reporting and Dissemination	Preparation of research report and stakeholder presentations	Nov – Dec 2025

7. Financial Report and Grant Utilization

The research initiative was funded under the YouthAdapt Programme, a joint initiative of the African Development Bank (AfDB) and the Global Center on Adaptation (GCA). Garden House Youth Society was engaged as a sub-grantee and received a total grant of USD 100,000 to implement applied research on the role of IoT technologies in strengthening climate adaptation among smallholder farmers during Zambia's 2024 energy crisis.

The funds were utilized to support field-based research activities, technology deployment, data collection, farmer training, and dissemination of research findings. The project adhered to strict financial management procedures to ensure transparency, accountability, and efficient use of resources.

7.1 Overview of Grant Utilization

The grant was allocated across several key categories to support the successful implementation of the research project. Major expenditures included procurement of IoT monitoring equipment, field data collection, personnel costs, farmer training activities, and stakeholder engagement.
The project prioritized cost-effective implementation while ensuring that high-quality research outputs were generated. Resources were strategically allocated to maximize the impact of the research within the available funding.

7.2 Summary of Project Expenditures

Budget Category	**Description**	**Amount (USD)**
Personnel and Research Staff	Compensation for researchers, technicians, and field enumerators	38,000
IoT Equipment and Installation	Procurement of sensors, monitoring devices, and installation materials	22,000
Field Data Collection	Household surveys, data collection tools, and monitoring activities	12,000
Farmer Training and Capacity Building	Training workshops and technical support for participating farmers	9,000
Travel and Field Logistics	Transportation and field coordination across study sites	8,000
Data Analysis and Reporting	Data processing, report preparation, and documentation	6,000
Dissemination of Findings	Stakeholder workshops, publications, and communication materials	5,000
Total Grant Utilized		100,000

7.3 Financial Management and Accountability

Garden House Youth Society maintained a structured financial management system throughout the project. Key financial accountability measures included:

- Maintaining detailed financial records for all project expenditures

- Regular internal financial reviews to ensure compliance with the approved budget
- Proper documentation of procurement processes and receipts
- Separation of project funds from other organizational accounts

These measures ensured that project funds were used solely for approved research activities and that financial reporting remained transparent and verifiable.

7.4 Value for Money

The project delivered significant research outputs while maintaining efficient use of resources. By integrating technology trials with household surveys and stakeholder engagement activities, the research generated valuable insights into digital climate adaptation solutions for smallholder farmers.

The financial investment in this project contributed to improved understanding of how digital technologies can enhance agricultural resilience during climate and energy crises.

8. Research Findings and Analysis

This section presents the key findings from the applied research conducted to evaluate the effectiveness of Internet of Things (IoT) technologies in strengthening climate adaptation among smallholder farmers during Zambia's 2024 energy crisis. The findings are based on data collected from IoT sensors installed on solar-powered irrigation systems, household surveys conducted with participating farmers, and stakeholder consultations.

8.1 Performance of IoT Monitoring Systems

The installed IoT monitoring systems successfully collected real-time data on soil moisture levels, irrigation duration, water flow rates, and energy consumption of irrigation pumps. The sensors provided continuous data streams that allowed farmers and researchers to monitor irrigation activities and resource use more accurately.

Farmers reported that access to soil moisture data helped them determine when irrigation was actually required rather than relying on traditional guess-based methods. As a result, irrigation schedules became more precise and efficient.

The monitoring systems also helped identify periods when irrigation pumps were running unnecessarily or when water was being applied excessively.

8.2 Improvements in Irrigation Efficiency

Analysis of irrigation data showed that farms using IoT monitoring systems were able to significantly improve irrigation efficiency. Farmers adjusted irrigation schedules based on soil moisture readings, which reduced over-irrigation and improved water management.

On average, participating farms reduced irrigation water usage by approximately 25-30% without negatively affecting crop productivity. Improved irrigation management also contributed to better soil moisture balance and reduced water wastage.

These improvements demonstrate that digital monitoring systems can help optimize irrigation practices in smallholder farming systems.

8.3 Energy Efficiency and Reduced Pumping Costs

One of the key objectives of the research was to assess whether IoT technologies could improve energy efficiency in solar-powered irrigation systems during the national energy crisis.
Sensor data showed that optimized irrigation scheduling reduced unnecessary pump operation. As a result, farms using IoT monitoring systems experienced an estimated 20–25% reduction in energy consumption associated with irrigation activities.

Reduced pump usage also helped extend the lifespan of solar-powered irrigation equipment and reduced maintenance costs.

These findings highlight the potential for IoT technologies to improve the efficiency of energy use in agricultural systems, particularly during periods of energy scarcity.

8.4 Agricultural Productivity Outcomes

Despite reduced water and energy use, participating farmers reported stable or improved crop productivity during the research period. Improved irrigation scheduling ensured that crops received water at appropriate times, which enhanced plant health and reduced water stress.
Farmers cultivating vegetables and horticultural crops reported improved crop quality and more consistent yields. These improvements contributed to more stable farm incomes despite the challenging conditions created by the energy crisis.

8.5 Economic Benefits for Smallholder Farmers

Household survey results indicated that improved irrigation and energy efficiency helped reduce operational costs for participating farmers. Lower energy use and reduced water pumping requirements resulted in lower irrigation expenses.

Farmers also reported that improved crop productivity and quality enabled them to maintain market supply during the energy crisis, which helped stabilize household income.
These economic benefits demonstrate the potential of IoT technologies to enhance the financial resilience of smallholder farming systems.

8.6 Farmer Perceptions and Technology Adoption

Most participating farmers expressed positive perceptions of the IoT monitoring systems. Farmers appreciated the ability to monitor soil moisture conditions and irrigation activities using real-time data.

However, the research also identified several challenges related to technology adoption. These included:

- Limited digital literacy among some farmers
- Concerns about the cost of technology deployment

- Limited technical support in rural areas

Despite these challenges, many farmers indicated a willingness to continue using digital monitoring technologies if they were made more accessible and affordable.

8.7 Implications for Climate Adaptation

The findings suggest that IoT technologies can significantly enhance the adaptive capacity of smallholder farmers facing climate and energy challenges. By improving irrigation efficiency, reducing energy consumption, and supporting informed decision-making, digital monitoring systems enable farmers to manage resources more effectively during periods of environmental stress.

These results demonstrate that digital agriculture technologies can play an important role in strengthening climate resilience in smallholder farming systems.

9. Discussion and Policy Implications

The findings of this research provide important insights into the potential role of digital technologies in strengthening climate adaptation and energy resilience in smallholder agricultural systems. The results demonstrate that IoT-enabled monitoring systems can significantly improve irrigation efficiency, reduce energy consumption, and support better decision-making among farmers facing climate and energy challenges.

9.1 Digital Technologies as Climate Adaptation Tools

The study highlights the growing importance of digital technologies in supporting climate adaptation in agriculture. IoT monitoring systems provided farmers with real-time environmental data that enabled them to adjust irrigation practices and optimize water use. This improved decision-making capacity helped farmers manage limited water and energy resources more effectively during the national energy crisis.

These findings suggest that digital agriculture technologies can serve as practical climate adaptation tools that enhance farmers' resilience to climate variability and environmental shocks.

9.2 Strengthening the Energy-Water–Food Nexus

The research also demonstrates the interconnected nature of energy, water, and food systems in agricultural production. Zambia's 2024 drought exposed the vulnerability of agricultural systems that depend on reliable energy supply for irrigation and water management.

By optimizing irrigation schedules and reducing unnecessary pump operation, IoT monitoring systems helped improve the efficiency of both water and energy use. This highlights the potential for digital technologies to strengthen the energy–water–food nexus, which is essential for building resilient agricultural systems in climate-vulnerable regions.

9.3 Economic Implications for Smallholder Farmers

Improved irrigation efficiency and reduced energy consumption translated into tangible economic benefits for farmers. Lower operational costs and more stable crop productivity helped farmers maintain agricultural income despite the disruptions caused by the energy crisis.

These outcomes suggest that investments in digital agriculture technologies can generate economic returns by improving farm productivity and reducing resource waste.

From a policy perspective, supporting the adoption of digital monitoring systems could contribute to strengthening rural economic resilience while promoting more efficient use of natural resources.

9.4 Barriers to Technology Adoption

While the research demonstrated the potential benefits of IoT technologies, it also revealed several barriers to widespread adoption. These include limited digital literacy among farmers, high initial costs of technology deployment, and insufficient technical support infrastructure in rural areas.

Addressing these barriers will require coordinated efforts involving government institutions, development partners, and private sector technology providers. Programs that provide training, financial support, and technical assistance could help accelerate the adoption of digital agriculture solutions.

9.5 Policy Implications for Climate Adaptation and Digital Agriculture

The findings of this study have several policy implications. First, digital technologies should be recognized as important tools within national climate adaptation strategies. Integrating digital agriculture solutions into climate adaptation programs could help strengthen the resilience of smallholder farming systems.

Second, policies that promote access to affordable digital technologies and strengthen rural connectivity infrastructure will be essential for scaling these innovations.
Finally, partnerships between research institutions, technology developers, and agricultural extension services can help ensure that digital tools are designed to meet the needs of smallholder farmers.

Overall, the research demonstrates that IoT technologies can play a significant role in enhancing climate adaptation and energy efficiency in smallholder agriculture. With appropriate policy support and investment, digital agriculture innovations have the potential to transform climate resilience strategies in Zambia and across Africa.

10. Outcomes and Impact of the Research

The YouthAdapt-funded research initiative generated significant outcomes across technological, socioeconomic, and policy dimensions. By piloting IoT-enabled monitoring systems in smallholder farming environments during Zambia's 2024 energy crisis, the project demonstrated how digital technologies can strengthen climate adaptation while improving resource efficiency in agricultural systems.

10.1 Technological Innovation Outcomes

One of the key outcomes of the project was the successful deployment and testing of IoT-based monitoring technologies within solar-powered irrigation systems used by smallholder farmers. The sensors enabled real-time monitoring of soil moisture, irrigation activity, and energy consumption.

The results demonstrated that digital monitoring technologies can significantly improve irrigation management and energy efficiency in smallholder agricultural systems. The research also highlighted the practical feasibility of integrating IoT technologies into rural farming operations.

This innovation outcome provides valuable insights for scaling digital agriculture technologies as part of climate adaptation strategies.

10.2 Improved Resource Efficiency

Participating farmers were able to improve the efficiency of both water and energy use through data-driven irrigation management. Farmers used soil moisture information to schedule irrigation more accurately, which reduced water wastage and minimized unnecessary pump operation.
These improvements contributed to reduced operational costs and more sustainable use of natural resources. The findings demonstrate that digital technologies can support more efficient management of water and energy resources in climate-vulnerable agricultural systems.

10.3 Enhanced Climate Resilience for Farmers

The research showed that IoT monitoring systems can strengthen the adaptive capacity of smallholder farmers by improving their ability to respond to environmental and energy-related challenges. Access to real-time environmental data enabled farmers to make informed decisions regarding irrigation timing and water management.

This enhanced decision-making capacity helped farmers maintain agricultural productivity despite the disruptions caused by the energy crisis and drought conditions.

10.4 Economic Benefits for Rural Communities

The project also generated positive economic outcomes for participating farmers. Reduced irrigation costs, improved crop productivity, and more efficient energy use helped farmers maintain stable incomes during a period of economic uncertainty.

These economic benefits highlight the potential for digital agriculture technologies to contribute to rural economic resilience while supporting climate adaptation efforts.

10.5 Policy and Institutional Impact

The findings of this research provide important evidence for policymakers and development partners working on climate adaptation, digital agriculture, and rural development. The results demonstrate that digital technologies can play a key role in strengthening agricultural resilience to climate shocks and energy disruptions.

The research has contributed to policy dialogue on climate-smart agriculture and digital innovation in Zambia. The findings are relevant for national programs aimed at promoting climate adaptation and improving agricultural productivity.

10.6 Institutional Capacity Strengthening

Through the implementation of this project, Garden House Youth Society strengthened its institutional capacity in several areas, including:

- Applied research on digital agriculture technologies
- Field-based climate adaptation research
- Data collection and analysis using IoT monitoring systems
- Stakeholder engagement and policy dialogue

These strengthened capabilities position the organization to contribute to future research and innovation initiatives focused on climate adaptation and sustainable agricultural development.

11. Research Outputs and Deliverables

The YouthAdapt research initiative generated a range of knowledge products, datasets, and capacity-building outputs designed to support climate adaptation policy, digital agriculture innovation, and evidence-based decision-making. These outputs contribute to strengthening understanding of how IoT technologies can enhance resilience in smallholder agricultural systems.

11.1 Comprehensive Research Report

The primary output of the project is this comprehensive research report, which presents the methodology, findings, analysis, and policy recommendations arising from the study. The report documents the effectiveness of IoT monitoring technologies in improving irrigation efficiency, energy use, and agricultural productivity during Zambia's 2024 energy crisis.
The report will be published on the Garden House Youth Society website and shared with stakeholders including government agencies, development partners, research institutions, and agricultural organizations.

11.2 IoT Monitoring Dataset

The project generated a unique dataset based on the IoT sensors deployed in solar-powered irrigation systems. The dataset includes real-time information on:

- Soil moisture levels
- Irrigation duration and frequency

- Water flow rates in irrigation systems
- Energy consumption of irrigation pumps

This dataset provides valuable insights into the operational performance of digital irrigation monitoring systems in smallholder farming environments.

11.3 Household Socioeconomic Survey Dataset

The research also produced a dataset based on surveys conducted with 150 smallholder farmers participating in the project. The dataset includes information on:

- Agricultural production practices
- Energy use in farming systems
- Irrigation costs and water management practices
- Crop yields and farm income
- Farmer perceptions of IoT technology adoption

This information provides a valuable resource for future research on digital agriculture and climate adaptation.

11.4 Farmer Training and Capacity Building

The project provided training sessions for participating farmers on the use of IoT monitoring technologies and climate-smart irrigation practices. These training activities helped farmers interpret soil moisture data and improve irrigation scheduling.
The training sessions also strengthened farmers' understanding of efficient water and energy management in agricultural production.

11.5 Stakeholder Engagement and Consultation Reports

Throughout the research process, the project organized consultations with key stakeholders including agricultural extension officers, local government representatives, farmer cooperatives, and development organizations.

Reports summarizing these consultations were developed to document stakeholder perspectives and policy recommendations related to digital agriculture and climate adaptation.

11.6 Policy Brief

A policy brief summarizing the key findings and recommendations of the research will be produced to inform policymakers and development partners. The brief will highlight practical policy actions that can support the adoption of digital climate adaptation technologies in Zambia's agricultural sector.

11.7 Knowledge Dissemination Materials

Additional communication materials were developed to share the project findings with broader audiences. These include presentation materials, stakeholder briefing documents, and outreach content designed to promote awareness of digital agriculture technologies.

Collectively, these outputs contribute to strengthening the knowledge base on digital climate adaptation solutions and provide evidence to support future investments in climate-resilient agriculture.

12. Limitations of the Study

While the research generated valuable insights into the role of Internet of Things (IoT) technologies in strengthening climate adaptation among smallholder farmers, several limitations should be acknowledged. Recognizing these limitations is important for ensuring transparency and for guiding future research and policy development.

12.1 Limited Duration of the Study

The research was conducted over a one-year period during Zambia's 2024–2025 energy crisis. Although this timeframe allowed the research team to observe the performance of IoT technologies under real-world conditions, it may not fully capture long-term impacts on agricultural productivity, resource efficiency, and technology adoption.

Long-term monitoring would provide deeper insights into the sustainability of IoT-based climate adaptation solutions.

12.2 Scale of Technology Deployment

The IoT monitoring systems were deployed in a limited number of farms within selected study areas. While the results provide valuable evidence on the potential benefits of digital monitoring technologies, the findings may not fully represent the diversity of agricultural systems across Zambia.

Future research involving larger-scale deployments across different agroecological zones would provide a more comprehensive understanding of technology performance under varying environmental conditions.

12.3 Connectivity and Infrastructure Challenges

Reliable internet connectivity remains a challenge in many rural areas of Zambia. Although the IoT systems used in this study were designed to function with limited connectivity, data transmission interruptions occasionally occurred in some locations.

Improving rural digital infrastructure will be important for supporting the widespread adoption of digital agriculture technologies.

12.4 Farmer Digital Literacy

The research revealed that some farmers initially faced difficulties interpreting the data generated by IoT monitoring systems due to limited familiarity with digital technologies. While training sessions helped address these challenges, digital literacy remains an important factor influencing the successful adoption of new technologies.

Programs that combine technology deployment with farmer training and extension support will be essential for scaling digital agriculture innovations.

12.5 Cost Considerations

The cost of deploying IoT technologies may present a barrier for widespread adoption among smallholder farmers. Although the research demonstrated that the technology can generate economic benefits through improved efficiency, the initial investment required for equipment and installation may be prohibitive for some farmers.

Future initiatives may need to explore financing mechanisms, subsidies, or cooperative models that can help reduce adoption costs.

12.6 Climate Variability

Agricultural production is influenced by multiple environmental factors beyond irrigation and energy use. Weather conditions, pest outbreaks, and soil characteristics may also affect crop productivity. As a result, isolating the exact contribution of IoT technologies to productivity improvements can be challenging.

Future studies incorporating climate modeling and larger datasets could help strengthen causal analysis.

Despite these limitations, the research provides important evidence on the role of digital technologies in improving resource efficiency and strengthening climate adaptation in smallholder agriculture. The findings offer valuable insights for policymakers, development partners, and technology innovators seeking scalable solutions to climate-related challenges in African agricultural systems.

13. Recommendations and Future Policy Directions

Based on the findings of this research, several policy and programmatic recommendations are proposed to strengthen the adoption of digital technologies for climate adaptation in Zambia's agricultural sector. These recommendations focus on improving access to digital agriculture solutions, strengthening farmer capacity, and integrating technology-based adaptation strategies into national climate and agricultural policies.

13.1 Promote Digital Agriculture within Climate Adaptation Policies

National climate adaptation strategies should explicitly recognize the role of digital technologies such as IoT monitoring systems in strengthening agricultural resilience. Integrating digital agriculture solutions into climate adaptation programs can support more efficient management of water, energy, and other agricultural resources.

Government institutions responsible for agriculture and climate policy should collaborate with research organizations and technology developers to promote digital innovation in climate-smart agriculture.

13.2 Strengthen Rural Digital Infrastructure

Reliable digital connectivity is essential for the effective use of IoT technologies in rural farming systems. Expanding rural internet coverage and improving digital infrastructure will enable farmers to access real-time environmental data and digital advisory services.

Investments in rural digital infrastructure should therefore be prioritized as part of broader strategies for agricultural modernization and climate resilience.

13.3 Support Farmer Training and Digital Literacy

Technology adoption depends not only on the availability of innovations but also on the ability of users to understand and apply them effectively. Training programs should be developed to improve farmers' digital literacy and technical skills.

Agricultural extension services can play an important role in supporting farmers' understanding of digital monitoring tools and climate-smart irrigation practices.

13.4 Improve Access to Affordable Technology

The cost of digital technologies remains a barrier for many smallholder farmers. Policymakers and development partners should explore financing mechanisms that make digital agriculture technologies more accessible.

Possible approaches include:

- Subsidy programs for climate-smart technologies
- Cooperative ownership models for digital equipment
- Partnerships with private sector technology providers

These approaches can help lower adoption barriers and accelerate the diffusion of digital innovations.

13.5 Strengthen Partnerships between Technology Developers and Farmers

Collaboration between technology developers, agricultural researchers, and farming communities is essential for designing solutions that meet the needs of smallholder farmers. Pilot programs and participatory technology development initiatives can help ensure that digital tools are user-friendly and adapted to local conditions.

Such partnerships can also help identify practical challenges and opportunities for improving technology performance in rural environments.

13.6 Encourage Investment in Climate-Smart Agricultural Innovation

Development partners and climate finance institutions should consider increasing investments in digital climate adaptation technologies. The results of this study demonstrate that IoT-based monitoring systems can deliver tangible benefits in terms of resource efficiency and agricultural productivity.

Supporting innovation in digital agriculture can contribute to strengthening climate resilience while promoting sustainable economic development in rural communities.

13.7 Expand Research on Digital Climate Adaptation

Further research is needed to better understand the long-term impacts of digital technologies on agricultural productivity, water management, and rural livelihoods. Future studies could examine the performance of IoT technologies across different crops, agroecological zones, and farming systems.

Such research would help generate stronger evidence for scaling digital climate adaptation solutions in Africa.

14. Conclusion

Zambia's 2024 drought and the resulting national energy crisis exposed the vulnerability of agricultural systems that depend on stable environmental conditions and reliable energy supply. Smallholder farmers were particularly affected, as disruptions in electricity supply limited irrigation capacity, increased production costs, and threatened agricultural productivity.

This research, supported by the YouthAdapt Programme of the African Development Bank (AfDB) and the Global Center on Adaptation (GCA), examined the role of Internet of Things (IoT) technologies in strengthening climate adaptation among smallholder farmers during this period of crisis. By deploying IoT monitoring systems in solar-powered irrigation systems and conducting field-based analysis, the study generated practical evidence on how digital technologies can support more efficient resource management in agriculture.

The findings demonstrate that IoT technologies can significantly improve irrigation efficiency, reduce energy consumption, and support better decision-making among farmers. Access to real-time soil moisture and energy monitoring data enabled farmers to optimize irrigation schedules, reduce unnecessary pump operation, and improve crop productivity despite the challenges created by the energy crisis.

The research also showed that digital monitoring technologies can enhance the economic resilience of smallholder farmers by reducing operational costs and improving the reliability of agricultural production systems. These benefits are particularly important in climate-vulnerable regions where farmers face increasing uncertainty due to droughts and other environmental shocks.

However, the study also highlighted several challenges that must be addressed to scale digital agriculture technologies. These include limited digital literacy among farmers, connectivity constraints in rural areas, and the relatively high cost of technology deployment.

Addressing these barriers will require coordinated efforts involving governments, development partners, technology providers, and research institutions. Policies that promote digital infrastructure development, farmer training, and affordable access to climate-smart technologies will be essential for expanding the adoption of digital agriculture innovations.

Overall, this research demonstrates that IoT technologies offer a promising pathway for strengthening climate adaptation in smallholder agriculture. By improving the efficiency of water and energy use and supporting data-driven decision-making, digital technologies can play a critical role in building more resilient agricultural systems in Zambia and across Africa.

The insights generated by this study contribute to the growing body of evidence supporting the integration of digital technologies into climate adaptation strategies for agriculture. These findings provide valuable guidance for policymakers, development partners, and investors seeking scalable solutions to address climate risks and strengthen rural economic resilience.

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