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SELF-SUSTAINING IOT NETWORKS AND AI-DRIVEN ENERGY HARVESTING FOR SMART AGRICULTURE

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Abstract

The growing need of sustainable farming methods has prompted the use of Internet of Things (IoT) technology in precision farming. IoT devices to traditional sources of power however is a key obstacle to scalability and long term deployment particularly in remote or resource constrained farming regions. This paper discusses the integration of self-sustaining IoT networks to optimize energy harvesting opportunities and artificial intelligence (AI)-driven energy optimization strategies to attain agricultural efficiency and resiliency. The qualitative research design, which was used to collect the data, was semi-structured interviews and focus group discussions with farmers, technology specialists, policy makers and agribusiness representatives. Thematic analysis revealed that self-sustainable IoT systems where the stakeholders perceive the systems to be highly useful in the improvement of crop monitoring, resource management and decision making. Being the possible solution to the constraint of the infrastructures, participants focused to the renewable energy harvesting and listed the cost, technical literacy, and trust in AI-based systems as the impediments. The findings show that although AI-based optimization has enhanced the autonomy and reliability of the IoT networks, the implementation of AI will only be successful with the assistance of positive policies, financial incentives, and capacity-building initiatives. The study is drawing a conclusion of the fact that self-sufficient IoT networks can be used to revolutionize smart agriculture to a new stage and instill low-maintenance, energy-saving and data-driven smart farming. It is recommended on the further development of large-scale adoption on the basis of collaborative relationships, demonstration initiatives, and a particular policy framework.

Introduction

The rapid development of the Internet of Things (IoT) has transformed the operations of industries and societies and agriculture remains one of the most appealing spheres of application. As the world population continues to rise, food demand will grow significantly and the agricultural systems should be more efficient, sustainable and more adaptive (Rajappan et al., 2024). Despite maintaining relevance in certain cases, the traditional types of agriculture are becoming less and less able to face the challenges of climate change and the lack of natural resources, along with the demands of precision in crop control (Li et al., 2024). The integration of IoT-based solutions offers a groundbreaking approach to addressing these issues since IoT solutions have the potential to generate real-time monitoring, predictive analysis, and autonomous decision-making in farms. The concept of smart farming can be discussed as a very heavy reliance on IoT devices in order to collect and analyze such important data as soil sensors, drones, and automatic irrigation systems (SS et al., 2024). Not only are these systems contributing efficiency, but they are also assisting in minimizing wastage of resources, increasing crop yields and even ensuring food security in an environment that is rapidly changing (Edison, 2023).

Among all these opportunities, the energy dependency challenge has been one of the most demanding aspects of the implementation of the IoT systems in the agriculture industry. The IoT in farming is primarily implemented with conventional batteries or direct power, which limits the size, reliability, and costs. The adoption is not always possible in rural and resource-limited agricultural regions due to the possible lack of constant electricity or often needing to replace batteries (Kumar, 2024). The fact that the IoT is dependent on conventional sources of power is a flaw of the technology that should become something self-sufficient and independent indeed (Gouiza et al., 2024). In response to this, the research interest has starting to lean towards creating self-sustainable IoT networks, capable of utilizing ambient energy sources, such as solar, wind or thermal energy (Khan and Ullah, 2024). Such networks are able to reduce or even avoid the necessity to use external power supply, yet it is possible to equip the IoT devices with energy harvesting modules to increase their lifespan, decrease the maintenance costs, and make the work of agriculture more efficient (Szymański et al., 2024).

Artificial intelligence (AI) comes in to ensure that such systems become as efficient as possible. Smart operation of energy, predictive maintenance care, and adaptive response to environmental changes can be smartly implemented using AI on the basis of machine learning algorithms and optimization processes (Muserra & Khan, 2023). One of them is reinforcement learning, which allows systems to continue to improve strategies of energy allocation by learning through experience and neural networks can improve predictive performance according to environmental factors and the demands of energy (Kalyan et al., 2025). Finally, AI and energy-gathering IoT networks, therefore, offer a solution to developing robust, autonomous systems, which respond to the challenge of sustainability and productivity of agriculture.

Precision farming is a global initiative that is congruent with the integration of self-sustaining IoT networks within the context of agriculture (Iqbal, 2023). Precision farming aims at cutting down on wastage, optimizing the resource, and maximizing yield using adaptive farming to specific conditions and agronomic needs of the crop (Singh et al., 2024). The real-time information on soil moisture, temperature, humidity, and crop health will provide farmers with the opportunity to make decisions about using irrigation, fertilizer, controlling pests etc. The utilization of energy harvesting IoT devices can be used to supplement this strategy by ensuring the unresolved and autonomous data collection even in those regions where power infrastructure is less developed. This does not only enhance the reliability of agricultural monitoring systems but also reduces the cost of running it in terms of power regulation and maintenance of equipment (Shaheen, 2024).

Furthermore, one cannot overestimate sustainability in agriculture. The effects of climate change are increasing unsustainable agricultural methods which are fossil-based farming and high-consumption (Ghalim et al., 2025). The use of renewable energy sources in devices that make up the IoT to create self-sufficient networks will assist in reducing the carbon footprint and establishing more eco-friendly farming. This transformation is not only beneficial to farmers in terms of getting an economic benefit, but it also assists in achieving greater international ambitions of sustainable development goals (SDGs) (Afshar and Shah, 2025). The technologies can therefore be a key to sustainable agricultural transformation when implemented.

In addition to technical and environmental benefits, social and economic impact of self-sustaining self-organizing networks in agriculture are considerable. Self-sustaining IoT devices would provide access to unprecedented access to data-driven farming activities to smallholder farmers in developing nations, who in most instances are unable to access reliable power infrastructure (Saleem et al., 2025). The democratization of smart farming technology, in such a way, can help to bridge the gap between large-scale commercial farming and minor farming communities in order to establish a more equitable and inclusive agricultural innovation landscape (Jiang, 2024). The technologies could assist farmers in increasing productivity and resilience and mitigating risks to changing environmental conditions by reducing dependence on costly energy infrastructure (White & Scott, 2022).

However, self-sustaining AI-driven IoT networks have challenges of implementation. One of these challenges has been the cost factor since the initial cost or price of acquiring such systems may be too high to most farmers particularly in the developing regions (Mgendi, 2024). In addition, technical literacy problems, data privacy and system reliability problems also exist. When farmers lack trust in this technology or have no intention to lose control over the most significant aspects of farming processes, they may not be eager to apply AI-based decisions (Ullah et al., 2024). To address these problems, special policies, awareness and capacity building actions should be provided to ensure that farmers will be adequately prepared to adopt and enjoy the benefits of these innovations.

The growing literature base indicates the paradigm shift that the AI-based self-sustaining Internet of Things networks has, but the lack of empirical studies that investigate their application into the field of agriculture is evident. Field tests, prototype testing and stakeholder engagement are also an extremely significant part of understanding how viable, constrained, and expansive such systems can be (Vijayaregunathan et al., 2024). In addition, engineers, computer scientists, agronomists, policymakers, and farmers should collaborate with one another on an interdisciplinary basis to ensure the technology is technical and socially acceptable and economically viable (Hassan et al., 2024).

The given research is therefore going to contribute to the developing argument and provide the discussion of the ways in which the agricultural system based on the IoT can be combined with AI-based energy collection and optimization. Addressing the perceptions of the key stakeholders, the research will put into focus the opportunities, challenges, and the path to successful application of self-sustaining internet of things networks to smart agriculture. The findings are likely to provide knowledge that can be used to influence development of technology as well as policy making and ultimately assist in development of sustainable, effective and resilient farm systems. In such a way, it closes a great gap in the literature by connecting the technical development to the reality of farm work and offers an appropriate, healthy view of how AI and energy harvest can transform the future of farming.

Problem Statement

The application of IoT in agriculture has proven the immense potential of boosting efficiency and productivity, yet its reliance on conventional forms of energy is one of the main factors that hinder sustainable installation. Battery replacement is a common requirement and power supply is not always readily available and this limits scalability particularly in rural or resource strained regions. Energy harvesting is one of the solutions but the successful adoption should be optimized through artificial intelligence. This means that self-sustaining adoption of the IoT networks will not be common until the issues of cost, reliability, and awareness are sorted out, and this will frustrate their potential abilities of revolutionizing smart agriculture.

Literature Review

IoT in Modern Agriculture

Agricultural IoT applications have grown in the past few years and have enabled farmers to track crops, animals, and the environment in real-time. SOIL moisture sensors, climate monitors, automated irrigation systems have contributed immensely to decision making and resource efficiency. Smart agricultural systems provide farmers with a chance to modify interventions based on the prevailing circumstances that result in improved harvest and reduced wastage (Zerihun et al., 2022). The excessive dependence on the traditional sources of power to charge these gadgets is however a significant disadvantage especially in remote areas.

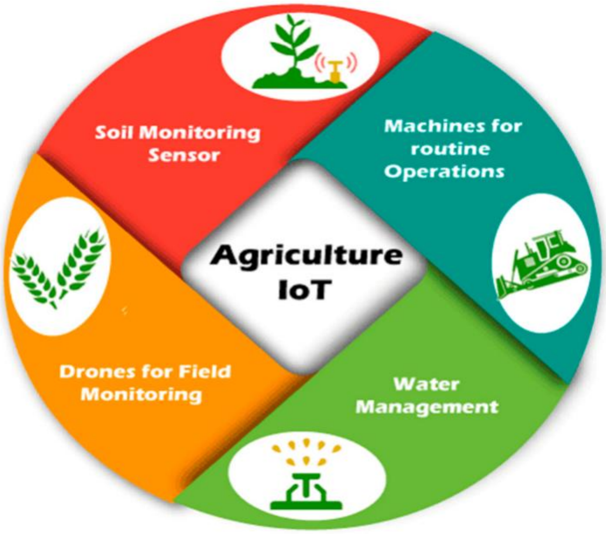

Figure 1: Agriculture IoT (Bouni et al., 2024)

Challenges of Energy Dependence

One of the most significant challenges of the IoT implementation in the agricultural sector is the use of batteries and grid power. The scalability of the IoT systems is being constrained by reliability of the power supply and regularity of battery replacement (Ikevuje et al., 2024). This challenge is particularly acute in underdeveloped areas or in rural locations, when sources of energy are not built. It is also a weakness to implementation because of the prices and the struggle to maintain battery-reliant devices of the IoT. In order to manage this problem, new energy technologies will be required, and they may enable them to work in a constant, autonomous mode with minimal human control (Chen et al., 2024).

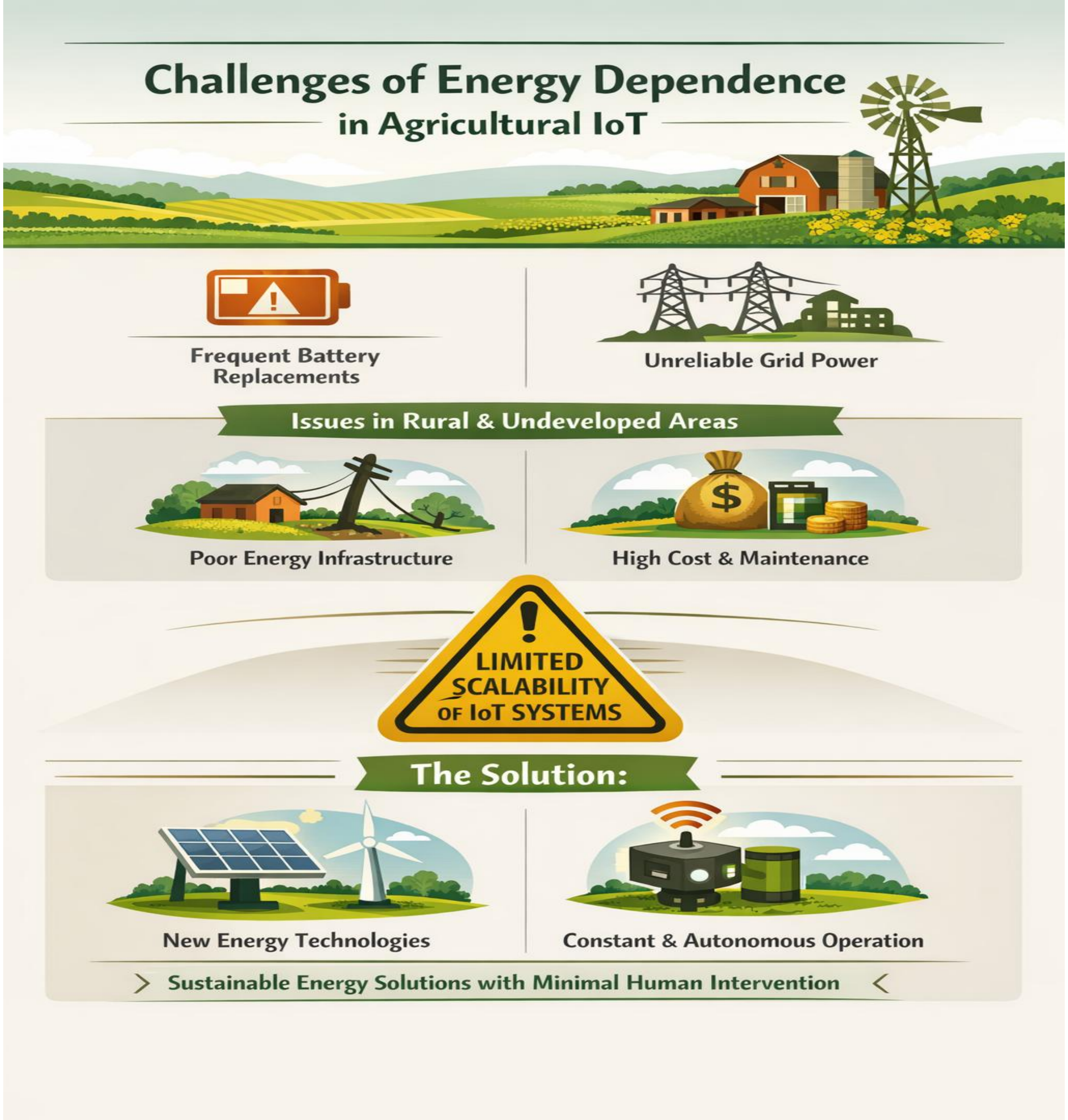

Figure 2: Challenges of Energy Dependence in Agriculture IoT

Energy Harvesting Solutions

Energy harvesting has also been a promising intervention to the energy dependency challenges in the IoT systems. Tools can be self-sustaining through the use of the available sources of energy in the environment e.g. solar, wind energy, thermal energy. The collection of solar energy, particularly, has been given an attention due to its abundance and it is possible within the agricultural set ups. The energy harvesting along with low-power IoT-based devices would lead to the extended lifecycle of the operation and lowering the maintenance costs (Zuo et al., 2023). Nevertheless, challenges associated with the creation of cheap and durable hardware that can be used to survive under the harsh conditions of farmland are still present.

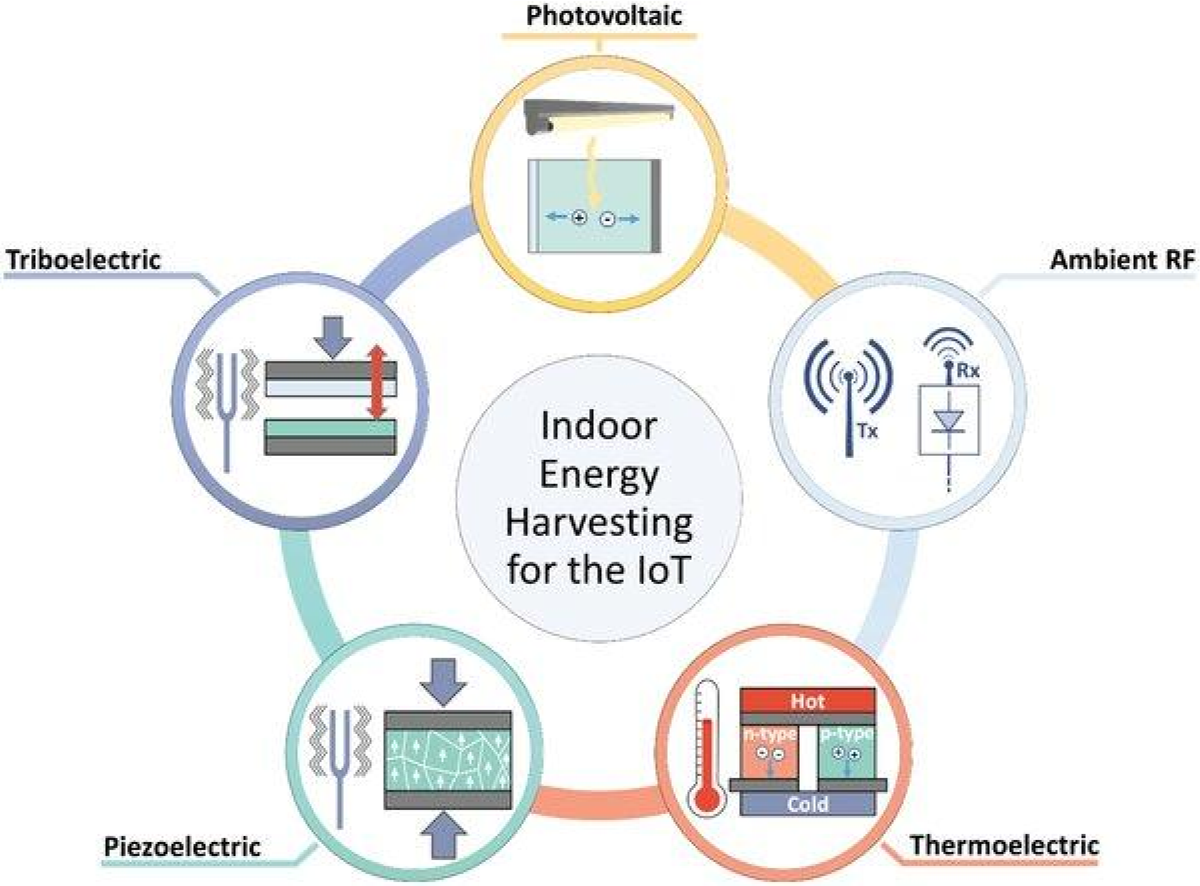

Figure 3: Energy Harvesting for the IoT (Pecunia et al., 2021).

Role of Artificial Intelligence in Optimization

The field of energy efficiency and sustainability of the IoT networks is becoming a major facilitator by artificial intelligence. Among the algorithms, reinforcement learning and neural networks can be used to optimize energy distribution, predict the necessity to be fixed and adjust to new environmental conditions (Nautiyal et al., 2024). With the implementation of AI, the IoT systems will be more autonomous and resilient. Artificial intelligence-based predictive models are also useful in enhancing agricultural decision-making because they predict the needs of irrigation, pest threats, and crop products. This integration of AI and energy collection is transforming IoT into not a passive data-gathering system but a proactive instrument to aid decisions (Shaikh et al., 2021).

Benefits for Precision Farming

Self-sustaining IoT networks offer a certain chance of precision farming where the optimization of resources is conducted at a micro-scale. The regular monitoring of the soil and crops condition and the environment makes it possible to implement relevant interventions, such as specific irrigation and fertilization (Raj et al., 2022). Farmers will be assured of real-time data with no breakages since the device will be able to keep running because of the power that can be generated by harvesting energy. Implementation of AI also introduces a higher degree of precision since the advice can be tailored to specific conditions of the crops and fields, leading to the improved yields and sustainability (Mizik, 2023).

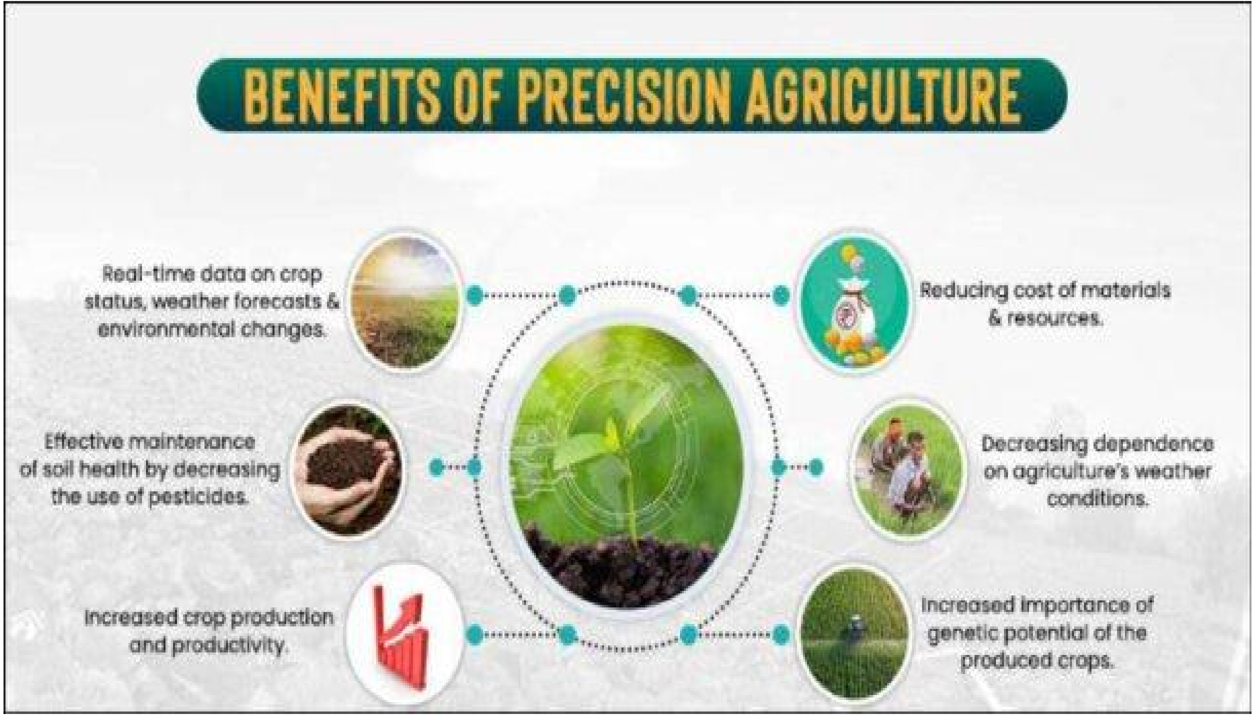

Figure 4: Benefits for Precision Farming (Satyam, 2024)

Challenges to Adoption

Despite the clear benefits, self-sustaining IoT networks in agriculture are faced with several challenges to their implementation. The greatest problem is high initial costs, especially among the smallholder farmers. Technical literacy is the other hurdle because some farmers may lack the skills to operate and maintain the innovative IoT systems (Long et al., 2016). The privacy of the data and reliance on AI-based decision-making also contribute to the resistance. Without the adequate training, support, and trust-building activities, farmers will not be interested in utilizing these technologies (Strong et al., 2022).

Figure 5: Challenges in technology adoption (Qureshi et al., 2022)

Policy and Institutional Support

Policymaking structure and institutional support is extremely significant in enabling utilization of innovative agricultural technologies. The government and pilot projects often require subsidies and training opportunities to reduce the financial barriers and to create the trust of farmers (Akella et al., 2023). It is also possible to develop and implement the self-sustaining IoT systems using the expertise of various stakeholders within the public-private partnerships. The technical feasibility is not the only issue of concern when developing an effective policy; the socio-economic reality is also important to ensure adoption is inclusive.

Future Insights

The future of agriculture is sustainable and data-driven, and self-sustaining IoT networks are well-positioned to achieve it. As the cost of hardware decreases and the availability of AI algorithms improves, the pace of such adoption systems is sure to increase. The ability to ensure that agricultural IoT devices have the ability to run continuously and autonomously will be relevant in achieving sustainability and productivity goals. IoT networks which are self-sustaining have the potential to revolutionize farming through appropriate policy interventions and collaboration with stakeholders and can be assimilated into global food security.

Main Objectives of the Study

1. To explore the potential of self-sustaining IoT networks in enhancing agricultural productivity and sustainability.

2. To examine the role of AI-driven energy harvesting and optimization in ensuring autonomous IoT device operation.
3. To identify challenges and barriers to the adoption of self-sustaining IoT systems in agriculture.
4. To analyze stakeholder perceptions regarding the feasibility and practicality of such technologies.
5. To provide recommendations for policy, research, and practice that can support large-scale implementation.

Methodology

This study adopted the qualitative type of research design to gain insights into the perception, experience, and problems of self-sustaining internet of things network adoption in smart agriculture. The semi-structured interview design was used, which provided the participants with the freedom to present their information in details, as well as allowed the researcher to delve deeper into the specific themes. The qualitative design was considered appropriate due to the fact that the study was intended to capture diverse views, practical challenges, and opportunities of AI-based energy harvesting in the agricultural environment in the future.

Participants and Sampling

The study participants were drawn from five key stakeholder groups:

1. Farmers and agricultural practitioners (small, medium, and large-scale)
2. Agricultural technology experts and IoT engineers
3. Government and policy stakeholders from agricultural and renewable energy departments
4. Agribusiness and smart farming solution providers
5. Academic researchers and agricultural extension officers

The convenience sampling approach was applied to choose individuals with a hands-on experience or knowledge of precision agriculture, IoT application or farm policy. It has involved a total of 25 people, with 10 being farmers, 5 technology experts, 4 policymakers, 3 business representatives, and 3 academic researchers. This variety played a central role in the fact that the user and the provider perspectives were taken.

Data Collection

Data was collected through semi-structured interviews and focus group discussions.

- ***Interviews:*** Conducted with farmers, experts, and policymakers to explore individual perceptions and experiences.
- ***Focus groups:*** Organized with farmers and extension officers to encourage interaction and collective reflection on barriers and opportunities for adopting IoT-driven sustainable systems.

Interviews ranged between 40-60 minutes and focus group between 60-90 minutes. Online and face to face two methods were used depending on the availability of the participants. Consent was recorded before each of the sessions on audio and transcribed into audio form.

Data Analysis

The study used thematic analysis to identify recurring patterns and themes within the qualitative data. Following Braun and Clarke's six-phase framework, the process involved:

1. Familiarization with data through repeated reading of transcripts
2. Generating initial codes based on key concepts such as *energy harvesting, AI optimization, barriers, opportunities,* and *future outlook*
3. Searching for broader themes by clustering similar codes
4. Reviewing themes to ensure consistency and accuracy
5. Defining and naming themes to reflect participants' perspectives

6. Producing the final report by integrating themes with existing literature

NVivo software was used to organize and code the transcripts, which enhanced systematic analysis and traceability of findings.

Ethical Considerations

The research followed an ethical norm to protect the rights and confidentiality of the participants. The participants were informed and assured that their responses can be utilized exclusively with an academic purpose. The reporting and transcription was carried out in an anonymous manner by concealing identities. The research design and instruments were reviewed and approved by institutional ethics committee and granted fieldwork.

Results

After semi-structured interviews and focus group discussions with farmers, agricultural technology experts, policymakers, representatives of the agribusiness, there were some common themes.

Perceptions of IoT in Agriculture

Most of the respondents cited the IoT as one of the handy devices in precision agriculture as a way of monitoring soil moisture, crop status and weather. The farmers explained that real time tracking would put real limits to wasting resources but the professionals indicated that it would raise the sustainable process of farming. An affordability and technical literacy problem was brought up but as the primary hindrances.

Attitudes Toward Energy Harvesting

Respondents agreed upon the fact that the possibility of using renewable energy (solar, wind, and thermal) was a promising prospect to powering the IoT systems in the farming industry in rural settings with a large degree of consensus. Farmers in remote areas have emphasized that self-sustaining machines can eliminate the issue of unstable electricity. Technology pundits insisted that such devices to capture energy be affordable and their performance has to survive extreme outdoor conditions.

AI-Driven Optimization and Reliability

The participants realised the capabilities of AI to streamline the use of energy and improve decision-making. The scholars emphasized that the reinforcement learning paradigms would be capable of reacting to the variable environmental factors, which would not interfere with the IoT activities. On the other hand, farmers were optimistically prudent and they stated that, there must be transparent interfaces, that are friendly to farmers and not completely reliant on human judgment.

Barriers to Adoption

Cost was always brought out as the most major barrier. Farmers believe that the government is supposed to offer subsidies and other forms of support to farmers who are not yet in a position to invest in their first IoT device and AI systems. The other policy observation was insufficient awareness and trainings that prevent massive adoption. In addition, policymakers and farmers also expressed the concern of the safety and reliability of AI forecasts.

Future Outlook and Opportunities

Most of the respondents conceived that the agricultural field would be revolutionized in the next 10 years due to the self-sustaining IoT networks supplying resource-efficient agriculture. They focused on the need to have pilot projects, government subsidies and joint ventures to make the technology affordable. According to the extension officers, the early adopters would establish some sort of trust and accelerate the diffusion process using farming communities.

Discussion

The findings indicate that the respondents acknowledge the transformative potential of self-sustaining IoTs in agricultural activities but highlight that socio-economic and infrastructural barriers should be eliminated

(Iqbal, 2023). This goes in accordance with the available literature, which has pointed out that cost, technical complexity, and awareness are some of the elements that slow the adoption of IoT in agriculture, particularly in the developing regions (White and Scott, 2022).

The popularity of the concept of energy harvesting is evidence that individuals concur that the problem of sustainability will be at the core of the innovative development of agriculture in the future (Saleem et al., 2025). Farmers, especially those in the remote areas feel that renewable energy can solve the intermittent power supply and this supports past studies that reveal that renewable integration is one of the factors contributing to the long-term adoption of the IoT.

The optimization of AI became a possibility and a problem. Its technical potential was established when the experts highlighted its flexibility and effectiveness. However, the fear of the farmers about overreliance on AI has shown the necessity to design the systems in a manner that would consider the decision-making algorithm by farmers and not to replace it. It suggests that the models of human-AI partnership could be more acceptable than fully automated systems in agriculture (Singh et al., 2024).

The barriers such as the cost, training and awareness are structural challenges that must be addressed. The farmers would be convinced through financial incentives to use energy-harvesting IoT networks although it comes with its benefits (Shaheen, 2024). The policies interventions as indicated by the government stakeholders follow the world trends where subsidies and capacity building programs have increased technology adoption in the agricultural sector (Zuo et al., 2023).

Participant prospects were optimistic, and they targeted pilot projects, demonstrating farms (Chen et al., 2024). It demonstrates that the success stories and the experiential learning could become influential in the establishment of perceptions and even the adoption rates (Afshar and Shah, 2025). In addition, the invitation to collaboration suggests that none of the participants (government, farmers, or providers of technology) can introduce this change alone; a joint ecosystem is needed.

Overall, the outcomes of the qualitative study allow concluding that self-sustainable IoT networks can be developed on the basis of energy optimization ensured by AI, however, the economic feasibility, the willingness of users, and the favorable policy will define the effectiveness of such solutions in the context of smart agriculture.

Conclusion and Recommendations

The findings of the current paper lead to the fact that one of the successful innovations that can be suggested in smart agriculture is the AI-powered energy collection that can be applied to enable self-sustaining IoT networks. These systems do not only extend the life cycle of devices employed in the IoT, but also assist in reducing costs and promoting environmental sustainability. By utilising renewable energy sources and implementing AI to become more autonomous and optimised, agricultural monitoring systems can be more autonomous and resilient and more efficient. The results indicate that such a form of networks may be applied to enhance the process of decision-making, to increase the level of resource distribution, and to stimulate the transition to the precision farming activities.

However, the paper also outlines significant barriers to adoption, including high start-up cost and technical illiteracy of farmers, but also fear of data privacy and lack of trust in AI-based decisions making. These problems show that technology is not the panacea to succeed but it needs to be supported by policies, training and cooperation of the stakeholders in order to be successfully implemented. The policymakers, technology developers and researchers must liaise with one another to work on solutions that are not only technical but also acceptable and economical in the eyes of the society.

It is also noted in this discussion that these innovations will be highly beneficial to the smallholder farmers when the issue of accessibility and affordability is put into consideration. Pilot projects and demonstration farms can be essential in proving the self-sustaining self-iot systems viability, building confidence with the users, and advancing the adoption development. Public-privacy partnerships and government subsidies can help cut the financial hurdles and training and capacity-building initiatives would facilitate farmers to adopt and exploit these technologies.

In conclusion, self-reliant IoT networks have the potential to revolutionize agriculture to create energy efficient, smart farming networks that require low maintenance. To implement this vision into practice, it is necessary to focus on cost-reduction, more publicity, and reinforced institutional support. Combining effort with the stakeholders through integration of AI-based energy efficiency and harvesting renewable energy, smart agriculture will advance to support a greater level of sustainability, resilience, and productivity, which in turn will enable the realization of the world food security and sustainable development goals.

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