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Optimizing Cluster Head Selection Algorithms to Improve Power Efficiency in Agricultural Wireless Sensor Networks

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Abstract: The current research addresses the management of Wireless Sensor Networks (WSNs) with a focus on optimizing power consumption, a critical concern in current research. The study uses agricultural WSNs to monitor farming areas, aiming to enhance decision-making in farm management. The importance of such monitoring systems in the region is emphasized. Previous research highlights clustering as an effective technique for power optimization, although it faces challenges, notably the selection of cluster heads responsible for data transmission. The Whale Optimizing Algorithm is cited as an example of a cluster head selection algorithm, which uses a fitness function considering node residual energy and the total energy of adjacent nodes. This research will analyze these algorithms and propose enhancements, particularly focusing on energy balancing. Additionally, it will conduct a study of agricultural networks, gathering data from existing agricultural WSNs. The analysis phase will involve using simulation software, primarily Matlab, to simulate and evaluate the proposed agricultural monitoring system.

Keywords: WSN, IOT, Optimization, Agriculture

Introduction

The Internet of Things (IOT) represents the current and future trend toward interconnected smart technologies. "Smart" refers to the integration of various applications that exchange data via electronics, software, sensors, and network connectivity to benefit human users. One significant application of IOT is the Wireless Sensor Network (WSN), the focus of current research, which is instrumental in developing decision support systems for solving real-world problems. WSN comprises a network of devices that collaborate to deliver services or products aimed at enhancing human life and facilitating critical decision-making. Its applications span diverse fields such as health, law enforcement, transportation, education, manufacturing, tourism, and agriculture (Aziz., *et al*., 2016; Tarapiah *et al*., 2013).

Despite the widespread adoption of WSN applications, they encounter several challenges including cost, bandwidth limitations, and most significantly, the optimization of power consumption remains a formidable issue (Singh and Gupta, 2013; He *et al*., 2024). Due to the limited power supply of WSNs, which is derived from batteries, it is necessary to optimize power consumption to a low level in order to extend the network's lifespan.

This research aims to investigate ways to reduce power consumption in Agricultural Wireless Sensor Networks (WSNs) designed for monitoring agricultural systems, to enhance decision-making for farm management. Typically, the network comprises 70 to 100 nodes, with one sink node responsible for collecting data from these nodes and transmitting it via an access point to the internet for analysis, facilitating optimal decision-making based on the readings. Each node consists of four components: Sensors, a radio transceiver, a microprocessor unit, and an energy source as depicted in Fig. (1).

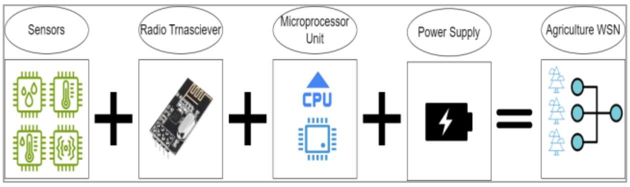

Fig. 1: WSN node

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Furthermore, the proposed WSN agricultural system consists of a set of WSNs with just one sink to collect data and transmit it to the internet as shown in Fig. (2), and then to the base station for processing and monitoring. This enables the end user to monitor and interact with the environment effectively.

Managing various types of sensors can be accomplished using a compatible sensor board as shown in Fig. (3). Such a board permits the connection of multiple sensors to a single node. Such sensors may include Light, Air Relative Humidity (RH), temperature, leaf RH, Soil moisture, soil humidity, scientific disease and Pest Monitoring, water irrigation, and fire sensors.

Table (1) displays the types and sizes of data for each sensor.

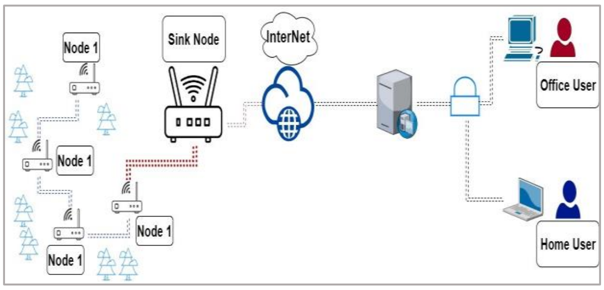

Fig. 2: Agricultural WSN

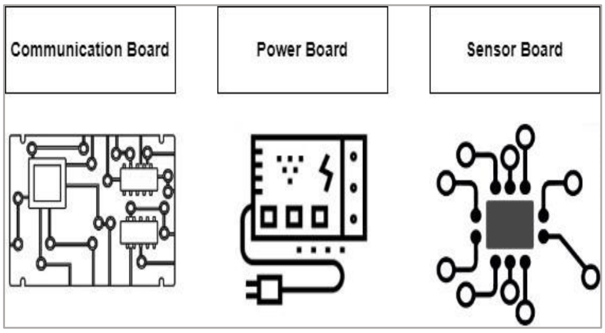

Fig. 3: Sensor Board

Table 1: Sensors data

Data	Data type	Data size (bits)
Monitoring water quality	Double	64
Soil composition	Double	64
soil humidity	Double	64
Light	Boolean	1
Wind speed	Float	32
Monitoring of diseases and pests	Boolean	1
Water irrigation	Boolean	1
Fire	Boolean	1
Total		228 Bits

Graph theory analysis will be applied to the proposed network, where sensor nodes represent nodes in the graph and the connections between them represent edges.

The routing protocol chosen is Low-Power and Lossy Networks (RPL), a distance-vector protocol based on IPv6. It is widely used in networks of this type and combines mesh and tree topologies, forming Destination Oriented Directed Acyclic Graphs (DODAGs) (Mishra *et al.*, 2024)

The significance of the application in regions like Palestine is underscored by the practices of occupation and settlers, which include preventing farmers from accessing their lands and causing tree burnings. Additionally, the agricultural sector has experienced a notable decline in recent years due to various factors such as climate change, decreased rainfall, and heightened soil drought. Moreover, agricultural lands near the occupation suffer from neglect and restricted access, contributing to these challenges. A figure illustrates how the agricultural sector's contribution to Gross Domestic Product (GDP) has decreased by 23% over the past two decades.

Figures (4-5) depict data for Palestine from 1994 to 2021 showing an average value of 9.16 percent. During this period, the lowest value was 6.32 percent in 2021 and the highest value was 13.26 percent in 1994. The most recent figure, from 2021, is 6.32 percent.

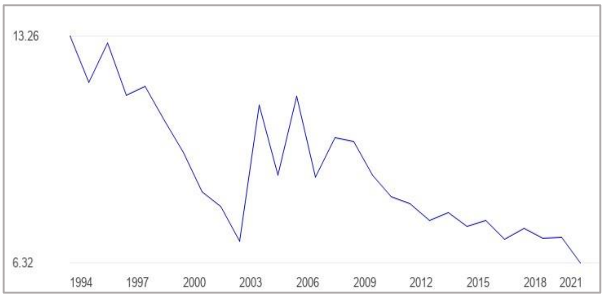

Fig. 4: The agricultural sector's contribution to the Gross Domestic Product (GDP) in Palestine between 1994 and 2021 (The World Bank, 2022)

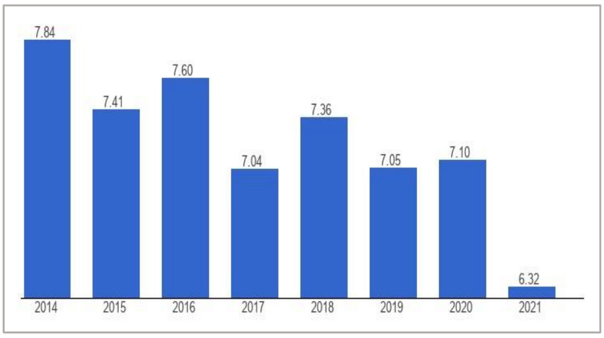

Fig. 5: The agricultural sector's contribution to the Gross Domestic Product (GDP) in Palestine between 2014 and 2021 (The World Bank, 2022)

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The proposed system aims to incentivize farmers and landowners who may lack sufficient time to manage their lands by offering automated monitoring. This means they do not need to physically be on their land every day. Wherever they are and whatever challenges they face, they can be confident that their farm operations are being monitored effectively. The system will monitor various metrics, including humidity levels to determine optimal irrigation timing. Additionally, equipped with fire alarm sensors, the system can promptly respond to any fire incidents that may occur (Dhanaraju *et al*., 2022)

Recent studies (Ishengoma and Athuman, 2018; Dibal *et al*., 2022), show that the implementation of the Internet of Things (IOT) and smart agriculture in several countries in Sub-Saharan Africa (SSA) has proven beneficial. These technologies have enabled farmers to increase crop yields throughout the year, enhance their living standards, and boost the economies of these nations.

In Wireless Sensor Networks (WSNs), the average total power consumption is composed of four elements (Das *et al*., 2021): Low Power Mode, Central Processing Unit (CPU), Radio listening, and Radio transmitting. The power consumption rate in WSNs is influenced by the states of individual nodes and the network protocols used (Schandy *et al*., 2016) as depicted in Fig. (6).

Clustering is selected as the optimization technique for energy consumption in the proposed agricultural WSN a schematic description is stated in Fig. (7).

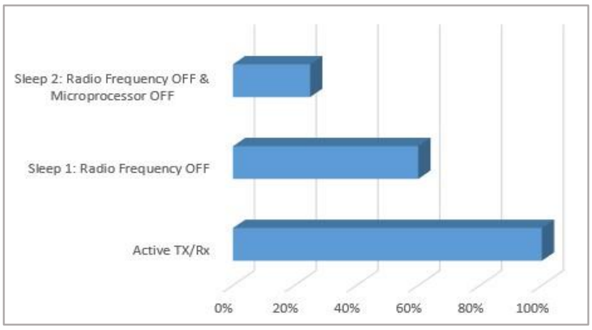

Fig. 6: Power consumption at different operational modes

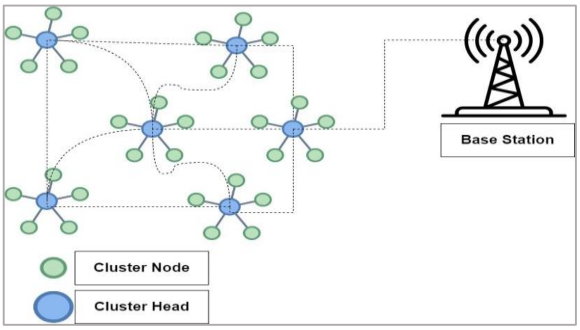

Fig. 7: Clustering in wireless sensor networks

The current study focuses on optimizing power consumption at the network layer based on data transmission requirements. Existing literature has suggested several techniques:

- Authentication Scheme-based power optimization technique: such technique is employed to remove injected invalid data from wireless sensor networks (WSNs) and conserve power. It utilizes a Message Authentication Code (MAC) to verify that the message originated from the expected sender and has not been altered during transmission, thereby providing assurance to the recipient (Thakare and Kim, 2021)
- Ant Colony Optimization (ACO) technique: ACO algorithms can be used to discover nearly optimal multi-hop routing paths in mobile ad hoc networks, such as AntHocNet. The key characteristic of ACO is stigmergy, which facilitates indirect coordination among agents (Farahmand-Tabar, 2024)
- Clustering: The cluster approach divides the entire network into several small clusters, each with its own cluster head responsible for processing, aggregating, and transmitting data among nodes within the same region. This approach has become increasingly significant in extending the lifespan of WSNs due to its methods for selecting cluster heads and aggregating data. Clustering continues to attract considerable research attention aimed at overcoming challenges like cluster head rotation and replacement, as well as improving intercluster and intracluster communication to enhance network longevity (Shilpa and Pushpender Kumar, 2016; Sahoo *et al*., 2024)

Choosing the optimal Cluster Head (CH) is a key challenge addressed in current research. Among the proposed algorithms for CH selection is the Whale Optimization Algorithm (WOA). WOA evaluates fitness functions to choose energy-efficient cluster heads, taking into account factors such as node residual energy and the cumulative energy of neighboring nodes. The research using WOA suggests future work focusing on additional factors like energy balancing (Azharuddin *et al*., 2015). Minimizing energy consumption often results in an uneven distribution of residual energy among sensor nodes, potentially leading to network partitioning (Kaleeswari and Baskaran, 2012).

The ongoing research aims to investigate various techniques while considering energy balancing.

Related Work

This section reviews several studies conducted in the literature related to Wireless Sensor Networks (WSN), primarily focusing on the challenges specific to agricultural applications.

Researchers have investigated the challenges facing WSNs in agricultural networks by analyzing existing networks in relation to current communication and networking technologies. They have also presented various case studies that categorize proposed solutions in the literature based on design and related parameters. Additionally, they have identified opportunities for improvement through the adoption of new technologies (Jadhav and Shankar, 2017; Aggarwal *et al.*, 2024).

In Mishra *et al.* (2024), researchers explored multiple approaches to studying power consumption in WSNs using different nodes and power sources, aiming to extend monitoring lifetimes. These approaches were discussed along with their respective features, highlighting the cluster technique as one of the suggested approaches. Clustering involves dividing nodes into small clusters, with each cluster collecting data from its members through a designated cluster head. The selection method for cluster heads is crucial in this context.

Efficient routing protocols in WSNs using cluster analysis were mentioned in (Humidi and Chowdhary, 2017) model. The review introduced basic routing protocols, their associated challenges, and proposed methods to address such challenges.

Researchers have also investigated algorithms for efficient energy-efficient cluster head selection, as this selection plays a crucial role in optimizing power consumption rates. They employed potential energy functions incorporating parameters such as intra-cluster distance, sink distance, and residual energy of sensor nodes during the cluster head selection phase. Various scenarios involving different numbers of nodes and cluster heads were tested to assess the effectiveness of that algorithm (Srinivasa Rao and Banka, 2017).

In Rita *et al.* (2017), clustering was proposed as a solution for energy optimization. The proposed mechanism suggested defining two cluster heads for each cluster in the network. One cluster head would handle communication with high-priority nodes, while the other would manage communications with nodes experiencing lower energy levels.

The Node Rank Algorithm (NRA) was also proposed by Al-Baz and El-Sayed (2018) for selecting cluster heads, based on the Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol (Ibrahim *et al.*, 2023). This algorithm demonstrated that cluster head selection could be based on path cost and the number of links between nodes, providing a systematic approach that overcomes random selection methods.

Moreover, Anisi *et al.* (2015) provide a comprehensive survey of various WSN approaches and their energy efficiency strategies for monitoring agricultural fields. Their study highlights the importance of optimizing energy use in sensor networks to enhance the longevity and effectiveness of precision farming systems.

To facilitate the transmission of large data such as images and videos through small sensor nodes, a study proposed a fuzzy cluster head selection algorithm. This algorithm considers three parameters: The node's remaining energy, the centrality of clusters, and the distance between nodes and the mobile sink (Wang *et al.*, 2018).

Wireless sensor networks often address uncertainty by integrating fuzzy logic into clustering algorithms. In the Fuzzy Clustering Algorithm (FCA) (Dinesh and Santhosh Kumar, 2024), fuzzy logic merges multiple parameters to identify a cluster head for WSNs. FCA employs the IF$_T$*HENruleforenhancedprecisionthroughthedefuzzificationoutputmethod.Anodewithastrongconnectiontoitsneighborsw.*

Materials

The experimental setup for this research involved the deployment of a Wireless Sensor Network (WSN) in an agricultural environment to evaluate power efficiency optimization techniques. The materials and equipment used in the study included:

- Wireless sensor nodes: A total of 100 sensor nodes were used, each equipped with sensors to measure environmental parameters such as temperature, soil moisture, air humidity, light intensity, and wind speed. These nodes were selected based on their low power consumption characteristics and ability to operate in outdoor conditions
- Microcontroller unit: Each sensor node was powered by a low-energy microcontroller, responsible for data processing and communication with the network
- Communication modules: The nodes communicated using IEEE 802.15.4-compliant transceivers, which provide low-power wireless communication. The network was configured to operate using a clustering-based communication model to optimize energy consumption
- Power supply: The sensor nodes were powered by lithium-ion batteries with an initial energy capacity of 0.5 Joules per node. To extend the operational lifespan, energy-harvesting mechanisms such as small solar panels were integrated into select nodes
- Base station and data processing unit: A base station, positioned at the center of the deployment area, collected sensor data. The base station was equipped with a high-performance processor and data storage units for real-time data analysis and transmission to the cloud for further processing
- Software tools: MATLAB was used for simulation and analysis of the proposed clustering algorithms. Additionally, Network Simulator 2 (NS2) was utilized to validate network performance under different clustering scenarios

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Methods

The methodology to be employed is the Waterfall Development approach, characterized by its sequential progression through several phases: Data collection, Design, Implementation, Verification, and Maintenance. The process flow diagram is depicted in Fig. (8).

More in detail, the methodology involved a set of phases as follows.

Data Collection Phase

The research methodology is a mixed quantitative and qualitative approach to encompass both numerical data and textual features. A descriptive approach will be employed to explore Wireless Sensor Networks (WSN) in relation to power optimization techniques and relevant algorithms. Primary and secondary data sources will be utilized to achieve the research objectives, including:

1. Primary data: The data will be derived from a literature review that incorporates opinions and experimental findings of other researchers. Additionally, researcher 148 will review journal articles, books, and recent reports focused on the relevant topic. Structured interviews will be conducted with farmers and employees from the research and development department of the Palestinian Ministry of Agriculture as part of the feasibility study for this research
2. Secondary data: The data used in this research are derived from the agricultural Wireless Sensor Network (WSN), which serves as the study case for applying the simulation model
    - Analysis phase data analysis will primarily utilize MATLAB software for simulation, with MATLAB code written in the C ++ programming language

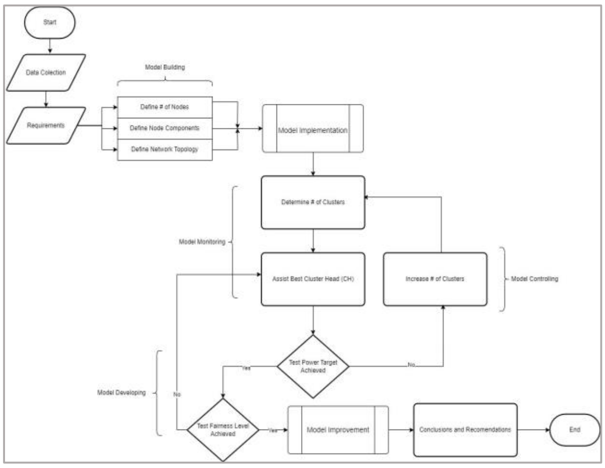

Fig. 8: Methodology flow-chart

- Development phase Based on the outcomes obtained in the preceding phase, targeted recommendations and actions will be executed utilizing insights gathered from the simulation

More methodological details, particularly on sampling and confounding variables are stated in Bashir *et al*. (2020), whereas the network setup module and the process module are stated, however, the network setup module includes the following:

1. Energy consumption model
2. Energy centroid
3. Gateway node
4. Cluster head joining weight function

where, as the process module, includes the following:

1. CH Selection phase
2. Gateway selection phase
3. Data transmission and CH rotation phase

Simulation Setup

This section presents the simulation parameters used in the experimental analysis of the proposed method. The simulations were conducted using Network Simulator 2 (NS2), a well-known and reliable tool for analyzing network routing and communication. The network covers an area of 100×100 m, with the base station located at coordinates [50, 50]. The simulation results were evaluated over different numbers of rounds, with each simulation round lasting 1000 units of time. The number of agricultural sensors is set at 100 and these sensors comprising temperature, light, soil moisture, location, and airflow sensors are randomly distributed. The packet size is set at 64 bits, with a payload size of 256 bytes. The energy required to operate a sensor's transmitter is uniformly 50 nJ. A Constant Bit Rate (CBR) is maintained between sensor nodes and the transmission 181 range of each sensor node is set to 20 m.

Results

The features of the provided system model are outlined below. First, we state the assumptions of the network model. To validate the design method, we use a randomized approach for a test network consisting of 100 nodes, covering an area of 100×100 m. The base station is located at coordinates [50, 50], with a probability value set at 0.1. Each sensor node has an initial energy of 0.5 J and all nodes start with the same energy state. During Cluster Head (CH) selection, each node has an equal probability of being chosen as a CH. The initial energy model for the nodes is based on Joules. The simulation continues until the radio equipment of any normal node fails. The algorithm allows for the deactivation of a node and the continued data transfer by other nodes. Additionally, all nodes and the sink remain in fixed positions, with similar computational and memory capacities. The network is considered homogeneous. The distance between nodes is calculated based on the received signal strength, meaning that sensor nodes do not need to know their exact positions. The following section describes the radio energy model.

The results of this study were obtained through simulation. FCA is recognized as a stable and energy-efficient WSN clustering algorithm. Given the similarity between our proposed method and the LEACH algorithm, we compared the two. Figure (9) displays the performance comparison between the FCA method and the LEACH algorithm, showing that FCA performs better.

Figure (10) further highlights the superiority and improvements of our proposed method. The simulation results reveal a 24% increase in the ratio of alive nodes with the proposed method compared to other methods. Figure (11) demonstrates that the proposed method is more efficient in terms of residual energy, extending the network's lifespan. The simulation results show a 9% improvement in the residual energy ratio for the proposed method.

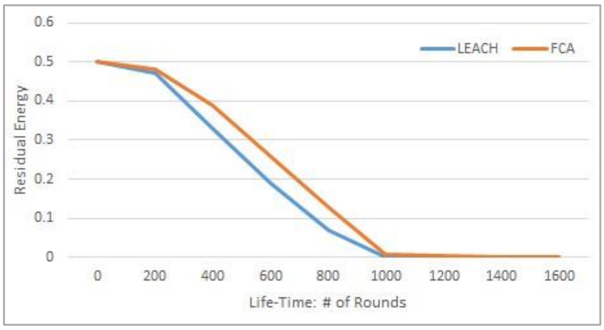

Fig. 9: Comparison of remaining energy in terms of lifespan and residual energy

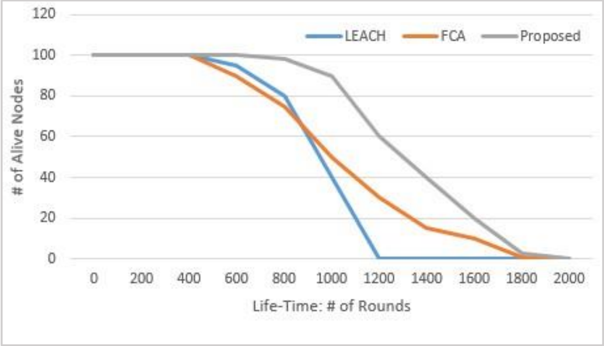

Fig. 10: Comparison of the number of live nodes between the LEACH, FCA algorithm and the proposed method

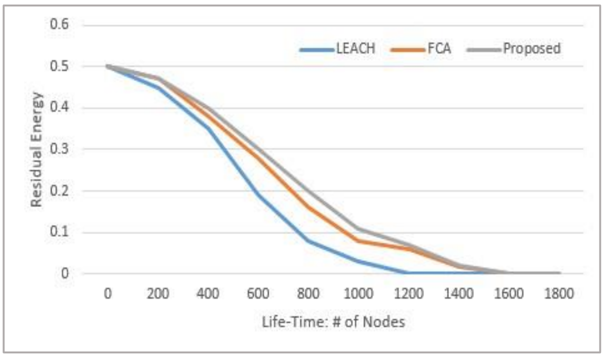

Fig. 11: Comparison of residual energy between the LEACH, FCA, and proposed algorithms

Discussion

The findings from this study demonstrate the effectiveness of the proposed clustering algorithm in enhancing the energy efficiency of agricultural WSNs. Compared to conventional methods such as LEACH and FCA, our approach significantly improves network lifespan and residual energy management. The observed 24% increase in the ratio of alive nodes and the 9% improvement in residual energy highlight the robustness of our clustering strategy.

Several studies have explored different clustering and routing techniques to optimize energy consumption in WSNs. For instance, Anisi *et al*. (2015) conducted a comprehensive survey of WSN approaches and emphasized the importance of optimizing energy use in sensor networks for precision agriculture. Similarly, Sahoo *et al*. (2024) proposed intelligent clustering methods to extend the network lifespan under uncertain conditions. Our findings align with these studies, reinforcing the role of clustering in energy-efficient WSN operations.

The novelty of our work lies in the enhanced cluster head selection process, which balances energy consumption more effectively across the network. Unlike previous methods that focus primarily on residual energy as a selection criterion (Al-Baz and El-Sayed, 2018), our algorithm integrates additional parameters such as intra-cluster distance and connectivity metrics to achieve better energy distribution. This approach mitigates network partitioning issues commonly observed in traditional clustering techniques.

Future research should explore the integration of machine learning techniques for dynamic cluster head selection, further optimizing energy efficiency in real-time applications. Additionally, testing the proposed algorithm in real-world agricultural environments will provide deeper insights into its practical applicability and performance under varying conditions.

Conclusion and Future Work

The study concludes that Wireless Sensor Networks (WSNs) are crucial for remote sensing in smart agriculture systems, playing a key role in monitoring temperature, irrigation, water supply, and more. These networks facilitate communication between various intelligent agricultural system components. WSNs comprise a network of nodes that interact with each other and a base station. Despite their potential, sensors face limitations such as topology management, mapping, organizations, and battery power, which negatively impact the performance of intelligent agriculture systems. Enhancing WSN quality can allow for remote data access, improving farm connectivity and coverage. To address issues like unreasonable cluster head selection and excessive power consumption, the study proposes an algorithm for intelligent agricultural system cluster head selection. The study included an evaluation and comparison of related technologies, demonstrating that the proposed method is more efficient than other existing solutions and enhances energy consumption, thereby extending the network lifetime.

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Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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