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Energy-efficient Solar-powered Wireless Sensor Network for Smart Agriculture

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ABSTRACT

Agricultural Surveillance requires constant collection of environmental data, including temperature, humidity, and soil moisture. Traditional wireless sensor networks rely mainly on batteries, which can necessitate frequent maintenance and replacement. This study suggests a Solar-Powered Wireless Sensor Network (SP-WSN) for smart agriculture that uses energy-efficient clustering, solar energy harvesting, and LoRa communication techniques. Solar energy harvesting supplies renewable power to sensor nodes implemented across agricultural fields. The sensor nodes obtain crop and environmental parameters and transfer the information utilizing a wireless communication network. An energy-efficient clustering and routing technique is utilized to balance the energy usage between sensor nodes and reduce unnecessary communication. A LoRa- based communication technique can be used to transmit low-power data across long distances between sensor nodes and the gateway. The Solar-Powered Wireless Sensor Network (SP-WSN) has been proposed to enhance energy effectiveness, communication consistency, and lifespan of the network. The performance assessment will take into account various factors including energy usage, length of time the network can run, packet delivery rate (PDR), time taken for remote transmission, amount of data sent, and remaining power supply. Performance of this technology should be evaluated according to specific procedures either through experiments or simulations in order to come up with stable measures.

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1. INTRODUCTION

WSNs are a network of independent sensor nodes[1] in an agricultural field that can monitor and collect data in real time from several locations utilizing a range of sensors, such as

temperature, humidity, soil moisture, light, and even cameras. This data is then wirelessly transferred to a central base station or gateway for further processing and analysis.

Agriculture plays a crucial part [2] in the production of food, requiring constant observation of field and environmental conditions. Continuous field condition monitoring is becoming more and more necessary in modern agricultural practices to assist crop management and the effective use of agricultural resources. Crop growth can be impacted by changes in variables including soil moisture, temperature, humidity, and other environmental elements. Agricultural monitoring uses sensor nodes that can acquire field information from different locations and transfer the collected data to a monitoring system.

Conventional agricultural monitoring techniques frequently depend on manual observation and sporadic measurements, which might not provide constant information about shifting field conditions. Sensing and communication technologies have been introduced by the development of smart agriculture, making it possible to monitor agricultural conditions more effectively.

An important drawback of wireless sensor networks [3] is the limited energy available at sensor nodes. Agricultural sensor nodes may be dispersed over comparatively vast areas, which increases the need for maintenance and makes routine battery replacement challenging. Consequently, the long-term operation of sensor nodes can be supported by renewable energy sources.

Solar Energy Harvesting is especially suitable for agricultural environments because solar radiation may be transformed into electrical energy to enhance wireless sensor nodes' power supply. Research focuses on approaches for minimizing reliance on traditional batteries and promoting sustained network performance.

Even though harvesting can provide more energy [4], network operation still requires the optimal use of the energy that is available. Energy-efficient clustering can aid in lowering communication-related energy consumption by arranging sensor nodes into groups. Clustering can decrease the amount of direct communication essential between individual sensor nodes and the gateway and can assist in distributing communication responsibilities within the network. An extensive analysis of energy-efficient WSNs for precision agriculture identified energy-efficient communication and clustering-related approaches as significant research directions for expanding the operational lifetime of agricultural sensor networks.

Another crucial prerequisite criterion in agricultural monitoring [5] is reliable communication over relatively large field areas while maintaining low power consumption. LoRa (long range) is a low-power, long-range wireless communication technology that's appropriate for applications involving small amounts of frequently transmitted sensor data for smart agriculture, including communication performance. This research aims to solve the issues of energy and communication regarding agricultural monitoring by proposing the Solar-Powered Wireless Sensor Network for Smart Agriculture (SP-WSN). This framework is based on three methods: solar energy harvesting, energy-efficient clustering, and LoRa communication. Solar power harvesting generates renewable energy for sensor nodes, energy-efficient clustering minimizes communication, and LoRa allows long-distance communication with low energy consumption. The evaluation of the suggested framework concerned energy usage, network longevity, packet delivery ratio (PDR), delay in communication, throughput, and remaining energy. The suggested system is examined using energy consumption, network lifetime, packet delivery ratio, communication delay, throughput, and residual energy. The overall analysis helps determine how effectively the suggested network can use renewable solar energy to sustain dependable long-range

communication and conserve sufficient residual energy for continued operation. This analysis gives an indication of the suitability of the proposed approach for continuous, reliable, and sustainable agricultural field monitoring over a prolonged duration.

2. LITERATURE REVIEW

For long-range agricultural communication, LoRa-based WSNs have been examined as a low-power communication solution. Suji Prasad et al. [6] developed a LoRa-based smart agriculture monitoring system in which sensor nodes communicate with a gateway to collect agricultural data. Their research shows how LoRa can support energy-efficient data transfer in agricultural monitoring environments.

De la Concepción et al. [7] exhibited an effective WSN platform that is ideal for agricultural applications and may be deployed in remote places. A sleep algorithm was proposed to reduce the WSN platform's energy usage. The findings demonstrated that the nodes are scalable, autonomous, and simple to find and move. However, due to the transceiver's omnidirectional antenna, the suggested system's communication range is constrained.

Nikolidakis *et al.* [8] proposed a novel Zigbee-based, energy-efficient routing protocol for WSN systems for automated agricultural irrigation system control and weather monitoring in the vicinity of agricultural fields. The suggested technology seeks to effectively and automatically manage the water supply in farmed fields. The system considers the historical data and changes in climate values to compute the quantity of water that is needed for irrigation.

Khan and Kumar [9] developed a low-cost routing path between two mobile sensor nodes. Additionally, they suggested a mobile sink traveling path algorithm to lower the energy consumption and delays of WSNs used for ambient agriculture field monitoring. WSN systems are effective for tracking animals and detecting their behavior, in addition to monitoring plants or soil in agricultural applications.

Loukatos et al. [10] demonstrated an IoT platform that combines several commercial soil measuring devices to observe how they behave in different scenarios while operating without interruption for extended periods of time. The same soil measurement tools were employed with two sensor nodes; one was buried and lacked solar power, while the other was set up on the ground with solar power. A variety of soil instruments were evaluated and presented with different calibrations. Both sensor nodes' power was tracked; the one without solar had a low battery, whereas the other remained saturated without dropping. Both nodes used 328 mW of power during transmission and 25 mW when they were idle. Applications for environmental monitoring, particularly those pertaining to soil, could benefit from the technology. However, the use of a multiplexer resulted in excessive power consumption.

Pitu et al. [11] demonstrated how to monitor IoT agricultural real-world applications using a low-power wide-area network (LPWAN) based on LoRaWAN technology. The NUCLEO-LRWAN1 and NUCLEO-L973RZ boards, which are energy-efficient devices with sophisticated humidity, temperature, and pressure sensors connected with an STMicroelectronics gateway, made up the system. With a communication range of 5 km (urban)/15 km (rural) for the end node and 10 km (urban)/30 km (rural) for the gateway, this system used 2.5 mW at the end node and 5 W at the gateway. However, the protocol, hardware constraints, and technological subtleties of LoRaWAN presented this system with a number of difficulties.

The studies analyzed indicate that wireless sensor networks, LoRa technology, energy-efficient routing, and solar energy harvesting become essential in farming. However, the findings from the studies are incomparable, meaning that they possess different system configurations, evaluation methodologies, and measurement metrics. To solve these difficulties, the contemporary research proposes an integrated SP-WSN methodology that considers solar energy harvesting, energy-efficient clustering, and LoRa technology. The conditions and the methods of evaluation need to be identified to ensure a proper comparison between standard WSNs and solar-powered WSNs that apply clustering.

3. METHODOLOGY

The SP-WSN framework proposed uses energy-aware clustering in order to group the sensor nodes and select their heads. The criteria used for cluster-head selection includes the remaining energy of each node, distance of communication and delay. The clustering algorithm groups sensor nodes based on the criteria mentioned. After gathering information from the member nodes, the cluster head collects the information and sends aggregated data to the gateway through the LoRa communication. While implementing the above-mentioned ideas, the clustering algorithm, input parameters, cluster-head selection method, stopping criteria and parameter settings should be described. The description must show the role of the optimized trilevel K-means algorithm in clustering and explain how energy and communication parameters are included in its work [12]. The overall architecture of the proposed framework is shown in Figure 1.

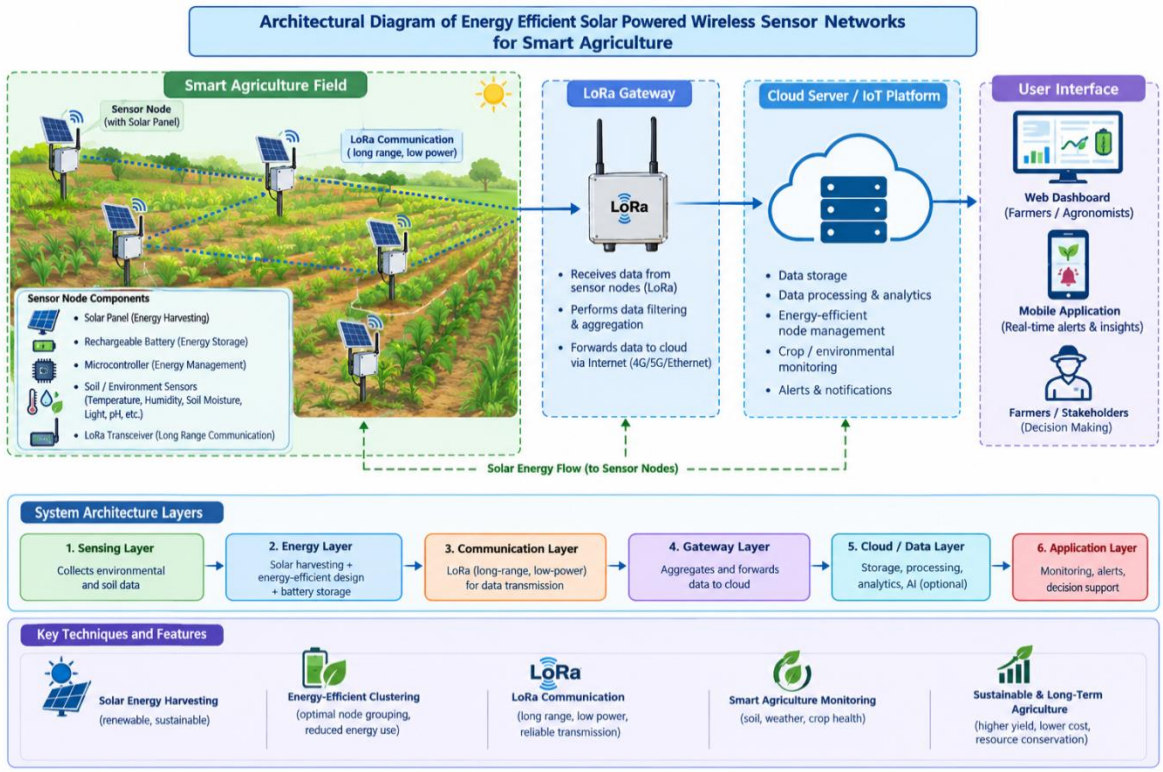


Figure 1. Architecture of the Proposed Energy-Efficient Solar-Powered WSN for Smart Agriculture

The proposed Energy-Efficient Solar-Powered Wireless Sensor Network (WSN) for Smart Agriculture is intended to provide continuous, reliable, and energy-efficient monitoring of agricultural fields. The architecture integrates wireless sensor technology, renewable solar energy, energy-efficient clustering, wireless communication, and farmer-oriented monitoring. The major

aim of the suggested architecture is to overcome the traditional wireless sensor network's restricted battery capacity and enhance agricultural monitoring systems' overall effectiveness. In the suggested system, in the agricultural area, several sensor nodes are placed so that environmental and agricultural conditions can be observed at various sites. Since agricultural fields can cover large areas, without requiring a lot of physical connections, the sensor nodes communicate wirelessly with the network infrastructure and with each other. The suggested architecture's basic sensing layer is made up of solar-powered sensor nodes. To obtain essential agricultural metrics including soil moisture, soil temperature, air temperature, humidity, light intensity, and crop conditions, many sensing components are present in every sensor node. A solar panel installed on the sensor nodes generates electricity from sunlight. This energy is stored in a rechargeable battery and is utilized to operate the sensor, processing, and wireless communication units. Depending on energy availability and system design, solar energy use can lower maintenance frequency and lessen reliance on traditional battery replacement. This is specifically useful in agricultural environments because sensor nodes may be dispersed over enormous areas.

The sensor nodes are arranged into clusters to increase energy efficiency. There are many regular sensor nodes and a Cluster Head (CH) in each cluster. The cluster head is essential to the gathering and processing of data from the cluster's sensor nodes. Instead of transmitting data directly from every sensor node to the base station, sensor nodes communicate with a nearby cluster head. When the gateway or base station send their data to the adjacent cluster head rather than to the main station, they can make the transmission distance less and conserve the required energy for communications. The cluster head assembles and combines the incoming data and sends it to the gateway afterward. While picking a cluster head, the analysis may take into account parameters like remaining energy, distance of communication, and transmission energy consumption.

Cluster heads can be chosen from nodes with adequate residual energy and good communication circumstances. Repeatedly, rotating or altering the cluster-head role can also prevent a small number of nodes from becoming overburdened and rapidly depleting their energy. The energy-efficient routing mechanism identifies the best route for sending data from sensor nodes to the base station**.** For instance, the cluster head can evaluate signals from multiple nearby sensors that show comparable soil moisture values and send a summary value rather than each reading. As a result, the network's operating lifetime can be extended, communication overhead is decreased, and energy consumption is minimized. Thus, the routing mechanism is crucial to the proposed system's accomplishment of its energy-efficiency goal. The solar energy management unit supplies a further benefit to the proposed architecture.

The harvested energy is stored in rechargeable batteries and utilized when the sensor nodes conduct communication and sensing tasks. An energy-aware approach can keep an eye on the amount of battery energy that is available and modify sensing or communication activities based on the node's energy situation. When adequate solar energy is available, nodes can perform normal sensing and communication. Reducing needless communication during times of low solar availability can help save stored energy. Consequently, the WSN's sustainability is enhanced and continuous network functioning is maintained when renewable energy harvesting and energy-aware communication are combined. The wireless sensor network and the external monitoring system communicate centrally through the Base Station (BS) or Gateway. The cluster uses the chosen communication channels to send its combined data to the base station.

The base station receives the agricultural data, performs initial processing, and passes the relevant information to a server platform. The gateway can be placed in an appropriate spot in a

large agricultural deployment to effectively sustain connectivity between the field network and the external network. As a result, the gateway offers a crucial link between the data-analysis and monitoring levels and the sensing layer in the agricultural field. The farmer monitoring application supplies the ultimate contact between the farmer and the suggested system. A web-based monitoring interface, mobile application, or computer dashboard can display the processed data. Farmers can observe real-time values of soil moisture, temperature, humidity, light intensity, and other factors without physically visiting every part of the agricultural field. The application can also generate alerts when a factor exceeds a predefined threshold. For example, the technology can alert the farmer that irrigation may be necessary if soil moisture drops too low. This promotes the effective use of water, energy, and other agricultural resources and enables farmers to make decisions more quickly and intelligently.

The proposed architecture is evaluated using several performance metrics, including energy consumption, network lifetime, Packet Delivery Ratio (PDR), communication delay, throughput, and residual energy. Overall, the proposed architecture provides a sustainable, reliable, and energy-efficient smart agriculture monitoring framework. The suggested WSN is appropriate for continuous and intelligent agricultural field monitoring since it is anticipated to produce lower energy consumption, higher residual energy, longer network lifetime, increased PDR and throughput, and decreased communication delay.

3.1 Solar Energy Harvesting

Each sensor node has a solar panel that converts sunlight into electrical energy. The harvested energy can be stored in a rechargeable battery and used either when solar radiation is absent or when the sensor is in operation.

A harvested-energy equation is:

$$E_h = P_{solar} \times \eta \times t \tag{1}$$

- $E_h = harvested\ energy$
- P_{solar} = accessible solar energy
- $\eta = efficiency\ of\ solar\ conversion$
- t = harvesting time

The energy that remains after harvesting can be expressed as:

$$E_{available} = E_{initial} + E_h - E_{consumed} \tag{2}$$

This helps establish whether a sensor node has adequate energy for continuous operation.

3.2 Energy-Efficient clustering

Energy-efficient clustering is an essential technique used in a Wireless Sensor Network (WSN) to reduce the energy consumption of sensor nodes and increase the overall network lifetime. In the smart agriculture field, numerous sensor nodes are used to gather data like soil moisture**,** temperature, humidity, and light intensity. A significant amount of energy is used if each sensor node transmits its data directly to the base station, particularly if there is a significant distance between the sensor nodes and the base station. The sensor nodes are divided into clusters; each cluster has a cluster head (CH).

In the proposed clustering approach, ordinary sensor nodes transmit their readings to their respective cluster heads rather than sending every packet directly to the gateway. Each cluster head receives and aggregates data from its member nodes and forwards the aggregated information to

the gateway through LoRa communication. This arrangement aims to reduce unnecessary long-distance transmissions and improve energy efficiency.

An energy model that is simplified can be written as:

$$E_{tx}(L, d) = L(E_{elec} + \varepsilon d^{n}) \quad (3)$$

Where:

- $E_{tx} = energy\ of\ transmission$
- $L = packet\ in\ length\ bits$
- $E_{elec} = energy\ in\ electrical\ circuits$
- $\varepsilon = amplifier$ coefficient
- d = transmission distance
- $n = \text{path} - \text{loss exponent}$

Thus, transmission energy consumption can be decreased by using clustering to lower the average communication distance. Similarly, the packet can be represented as the energy consumed:

$$E_{rx} = E_{elec}k \quad (4)$$

Thus, reducing unnecessary transmission distance and communication overhead can reduce the overall energy consumption of the network. The cluster head selection can consider factors such as residual energy and distance to neighboring nodes. A node can be chosen as the cluster head if it has enough energy left and an appropriate communication distance. This prevents low-energy nodes from being frequently selected and helps the nodes share the communication strain.

3.3 LoRa Communication

The proposed system used LoRa communication to transfer agricultural data over long distances while maintaining low- power operation. After sensing and local data aggregation, the cluster head transmits the aggregated information to the gateway through the LoRa link.

The following is an expression for the energy used during LoRa transmission:

$$E_{LoRa} = P_{tx} \times T_{tx} \quad (5)$$

Where E_{LoRa} is the transmission energy, P_{tx}, is the transmission, and T_{tx} is transmission time.

When a big agricultural field uses LoRa, fewer intermediate communication lines are required. Its long-range communication capability makes it appropriate for transmitting sensor data from distributed agricultural nodes to a central gateway.

3.4 Integrated operation of the proposed method

The three techniques work together as a single energy-aware communication process. First, the solar panel harvests energy from sunlight and stores it in the node's battery. The sensor nodes then monitor agricultural parameters and produce sensing data. Energy-efficient clustering assembles the nodes and selects appropriate cluster heads. Typical nodes transmit their information to the selected cluster heads, where data can be aggregated to reduce redundant transmissions. Finally, the cluster head uses LoRa communication to transmit the aggregate information to the gateway. Thus, the suggested approach aims to reduce communication-related energy consumption, enhance network lifetime, and ensure reliable agricultural data transmission.

4. COMPARATIVE ANALYSIS OF THE PROPOSED TECHNIQUES

A. Solar Energy Harvesting

In smart agricultural fields, solar energy harvesting is utilized to supply wireless sensor nodes with a sustainable energy source. Sunlight is converted by solar panels into electrical energy, which is then stored and utilized to run communication and sensor systems. This decreases dependence on conventional batteries and supports long-term network operation. The use of solar energy harvesting promotes the sustainability of energy concerning sensor nodes through sunlight conversion into electric energy. The paper should specify the parameter that is indicated by the 90% comparison value; as well as the means of its acquisition. Therefore, the 90% value cannot be understood as a proof of improved energy sustainability unless the method of evaluation is provided.

B. Energy-Efficient clustering

Energy-Efficient clustering is used to arrange sensor nodes into groups and decrease unnecessary communication between individual nodes and the base station. Cluster heads collect data from nearby sensor nodes and forward the aggregated information, consequently decreasing unnecessary energy consumption and transmissions. Energy-efficient clustering is indicated by 85% in the comparative graph. This demonstrates its suggested contribution to effective energy use. Clustering can help increase the wireless sensor network's operational lifetime by lowering the quantity of long-distance transmissions.

C. LoRa Communication

Long-range wireless transmission between agricultural sensor nodes and the receiving gateway is accomplished via LoRa communication. It is appropriate for smart agriculture because monitoring devices may be distributed over comparatively large field areas when reduced power usage and extended communication range are crucial. In the comparison graph, LoRa communication is represented by 83%. This suggested contribution toward reliable long-range communication with low power requirements with these percentage representation.

4.1 Comparison graph

The three techniques that have been implemented in the suggested system have been compared in terms of their percentage values and main contributions to smart farming. Solar energy harvesting helps in ensuring the provision of sustainable energy, energy-efficient clustering minimizes the energy consumption, and LoRa communication allows for long-range, low-power data transmission. The comparison of the values and the major contributions related to each of the techniques is given in Table 1 and Figure 2.

Table 1. Overall performance comparison of the three techniques

Technique	Percentage	Major Contribution
Solar Energy Harvesting	90%	Sustainable energy availability
Energy-Efficient clustering	85%	Decrease energy consumption
LoRa communication	83%	Long-range, low-power communication

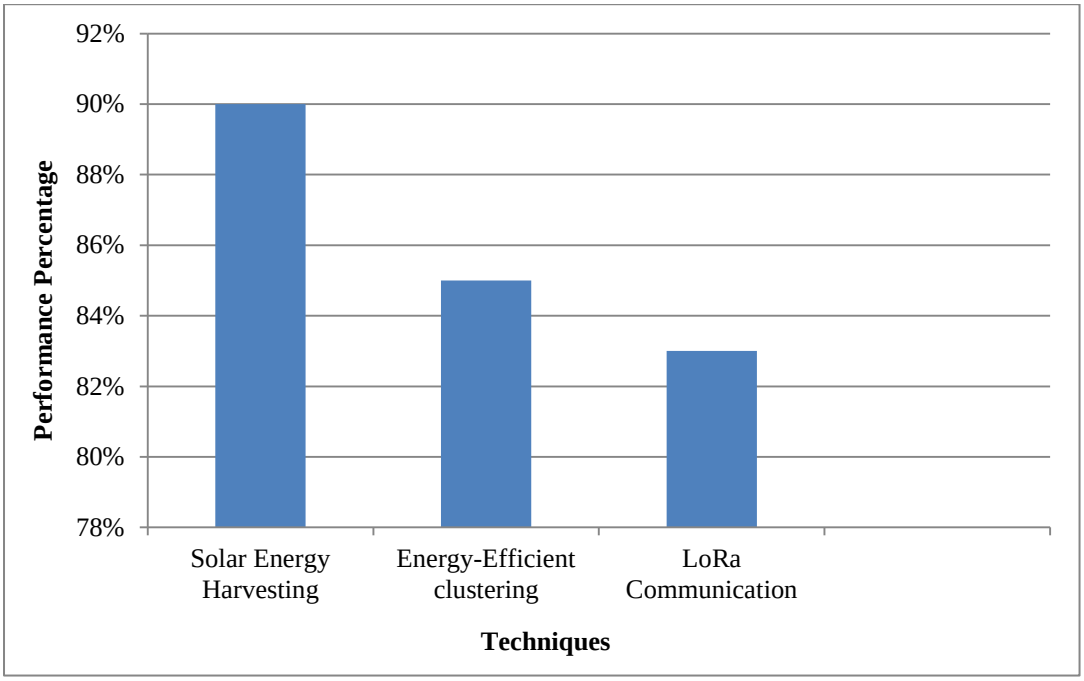


Figure 2. Percentage comparison of solar energy harvesting, energy-efficient clustering, and LoRa communication techniques for sustainable smart agricultural wireless sensor networks

5. RESULT AND DISCUSSION

An evaluation of the prescribed SP-WSN has been conducted based on 6 performance metrics: energy consumed, network lifetime, packet delivery ratio (PDR), communication latency, throughput and amount of energy left at the end of the study. The comparison is based on three systems which include the traditional WSN system, a solar-assisted WSN system with energy-efficient clustering, and the present SP-WSN assisted with energy harvesting from solar energy and energy-efficient clustering, and LoRa communication. The observed values are compiled in Table 2. The experimental or simulation process and normalization of the data and method for calculation of each metric should be presented for reproducibility and interpretation of the results.

Table 2. Comparative analysis of performance metrics

Metric	Conventional	Solar+ clustering	SP-WSN	Better
Energy consumption	90%	68%	48%	Lower
Network lifetime	65%	80%	94%	Higher
PDR	83%	90%	96%	Higher
Communication delay	98%	80%	63%	Lower
Throughput	75%	88%	99%	Higher
Residual energy	35%	54%	70%	Higher

5.1 Energy consumption

Energy consumption signifies the total energy used by sensor nodes for sensing, processing, transmission, reception, and clustering operations.

$$E_{total} = E_{sense} + E_{process} + E_{tx} + E_{rx} + E_{cluster} \quad (6)$$

Where E_{sense} is sensing energy, $E_{process}$ is processing energy, E_{tx} is transmission energy, E_{rx} reception energy, and $E_{cluster}$ is clustering-related energy.

Lower energy consumption reveals more efficient utilization of the available energy

Figure 3 illustrates the energy consumption of the existing Wireless Sensor Network (WSN), solar-powered WSN with clustering, and the new system of SP-WSN. The comparative normalized values of energy consumption are reported to be 90%, 68%, and 48%, respectively, indicating the proposed SP-WSN attains an energy-saving of 42 percentage points compared to the conventional WSN. This comparison suggests an energy saving of about 46.7%. This statement could be made with respect to normalized values and cannot be referred to as measured energy savings unless corroborated with relevant information.

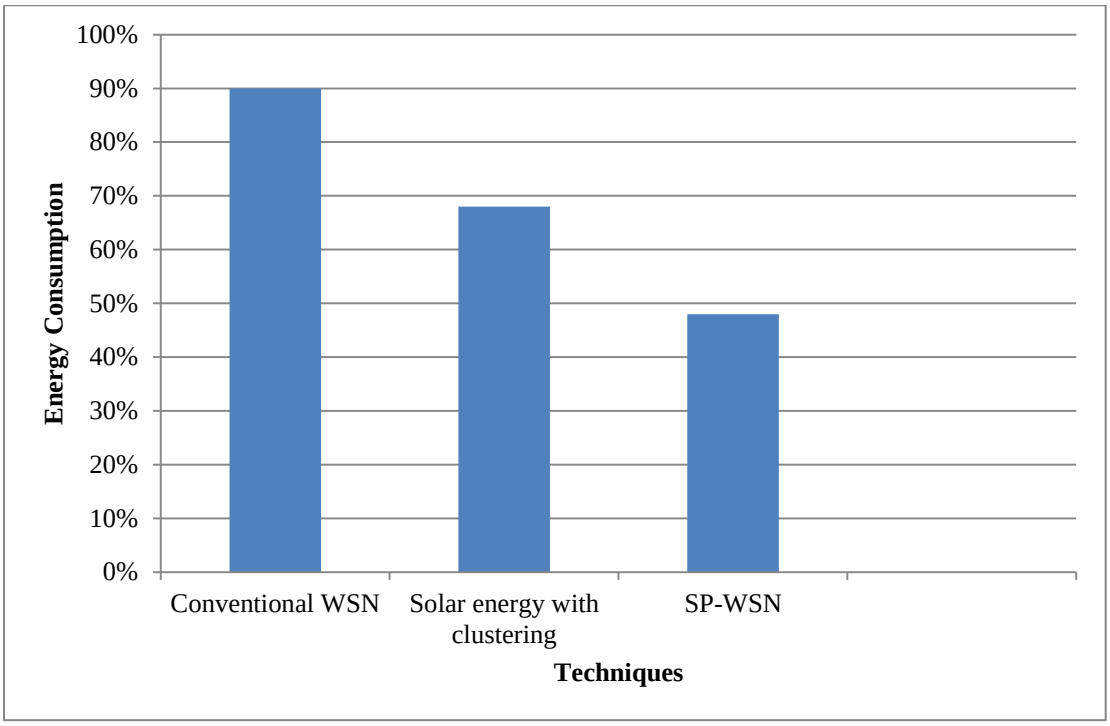


Figure 3. Percentage-based comparison of energy consumption among three approaches

5.2 Network Lifetime

Network Lifetime depicts the duration for which the network of wireless sensors remains operational.

$$NL = T_{network_end} - T_{network_start} \quad (7)$$

Where $T_{network_start}$ is the start of network operations and $T_{network_end}$ represents when the network achieves the specified failure condition.

An extended lifetime of the network implies that the suggested method can maintain sensor-node operation for a longer period.

In Figure 4, The suggested method (SP- WSN) normalizes network lifetime by 94%, compared with 65% for conventional WSN. While effective clustering minimizes wasteful energy use, solar energy collection constantly supplies sensor nodes.

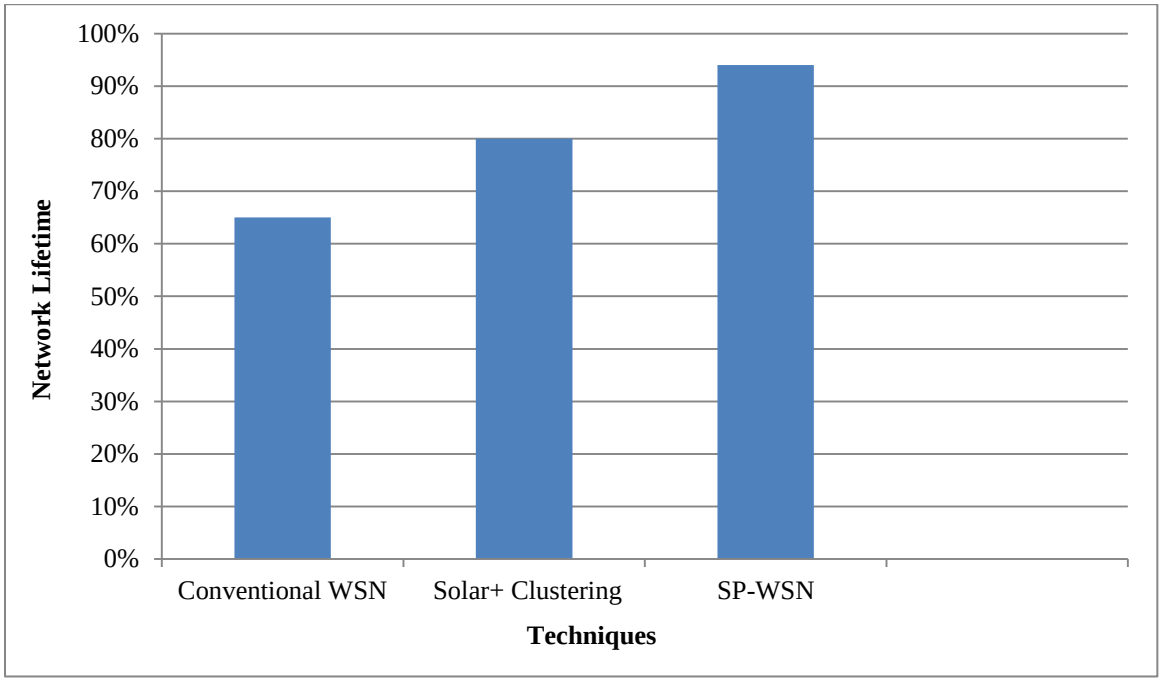


Figure 4. Percentage-based comparison of network lifetime among three approaches

5.3 Packet Delivery Ratio

Packet Delivery Ratio determines the percentage of transferred packets that are successfully received by the gateway.

$$PDR(\%) = \frac{N_{\,received}}{N_{sent}} \times 100 \quad (8)$$

Where $N_{\,received}$ is the quantity that the gateway has successfully received packets and N_{sent} is the total number of transferred packets.

A higher PDR indicates fewer packet losses and more dependable LoRa communication.

In Figure 5, The proposed approach (SP-WSN) achieves 96% packet delivery ratio, compared with 83% for conventional WSN. This suggests that data transmission reliability in agricultural sensing situations has improved.

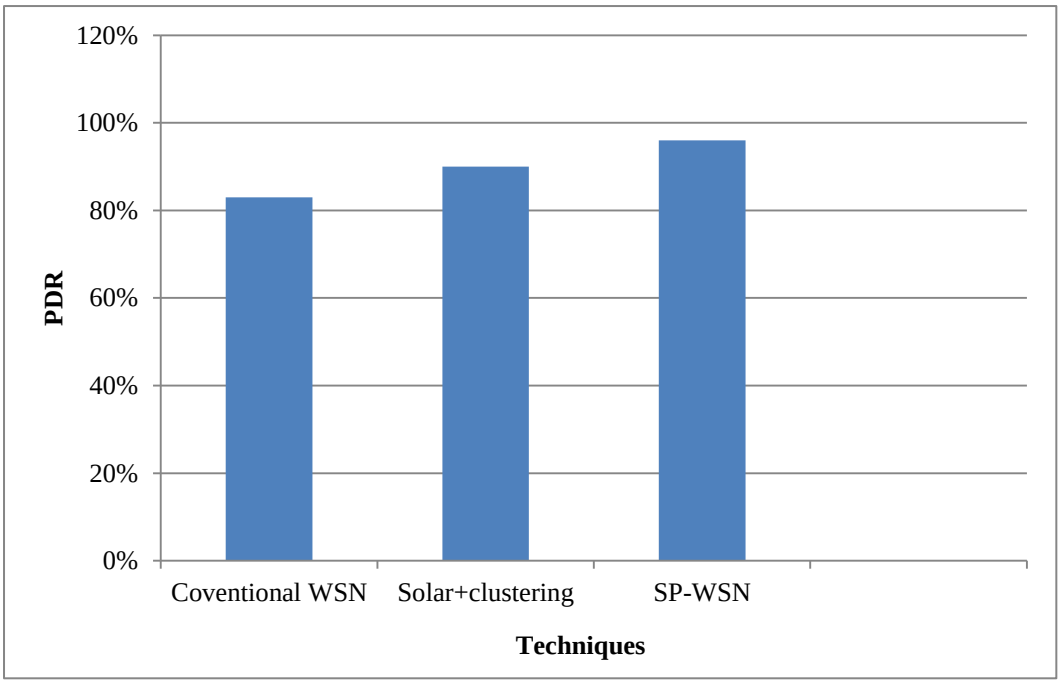


Figure 5. Percentage-based comparison of packet delivery ratio among the three approaches

5.4 Communication Delay

Communication delay methods the time taken for a data packet to travel from the sensor node to the receiving gateway.

$$D = T_{received} - T_{sent}(9) \quad (9)$$

Where $T_{received}$ is the packet reception duration and T_{sent} is the packet transmission time.

Faster delivery of agricultural sensing data is indicated by a lower latency.

In Figure 6, The proposed approach (SP-WSN) decreases normalized communication delay 63%, compared with 98% for the conventional WSN. This illustrates a 35% decrease in latency, enabling quicker data transfer.

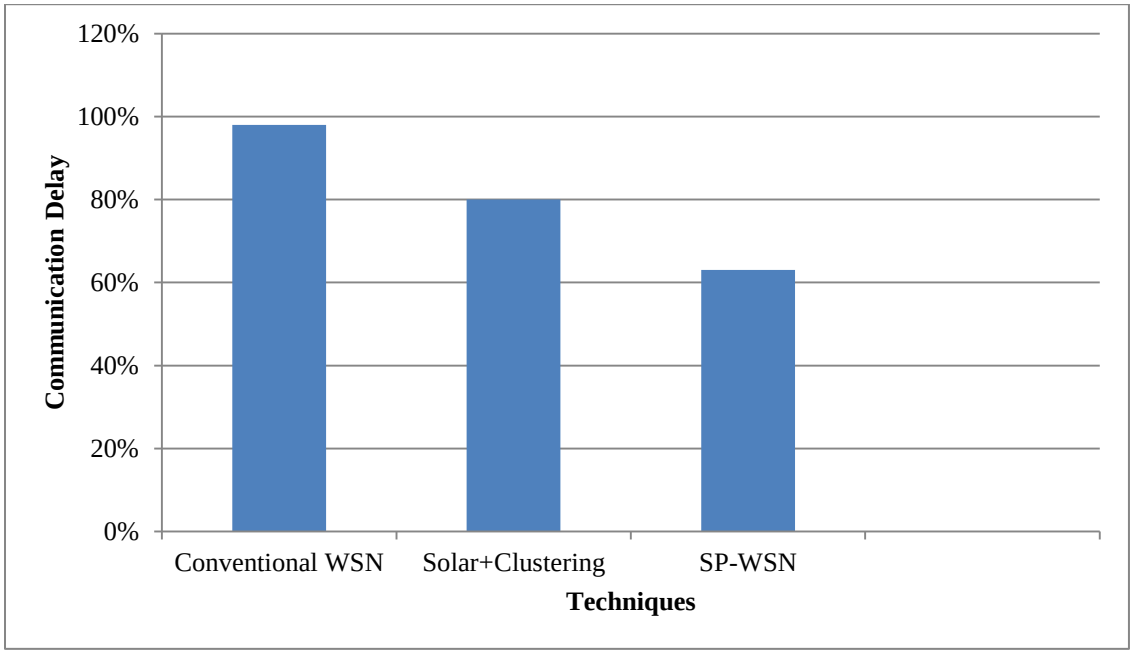


Figure 6. Percentage-based comparison of communication delay among three approaches

5.5 Throughput

Throughput represents the quantity of valuable information effectively provided through the network during a specific period.

$$\text{Throughput} = \frac{D_{received}}{T_{simulation}} \quad (10)$$

Where $D_{received}$ is the total successfully received data and $T_{simulation}$ is the observation or simulation duration.

Higher throughout suggests more effective data transference through the LoRa communication network.

In Figure 7, The proposed approach (SP-WSN) achieves 99% throughput is normalized, higher than 75% for conventional WSN. Effective clustering minimizes redundant communication, and LoRa facilitates dependable long-distance data transfer.

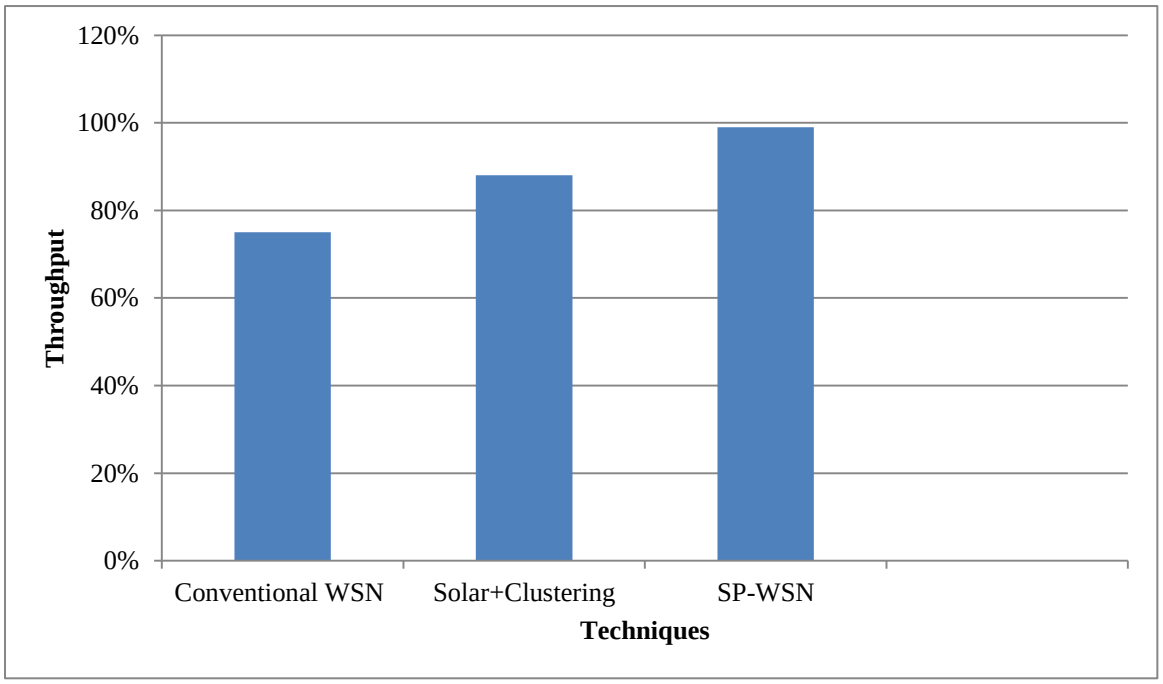


Figure 7. Percentage-based comparison of throughput among three approaches

5.6 Residual Energy

The energy that remains in a sensor node after its sensing, processing, and communication tasks are finished is known as residual energy.

$$E_{res} = E_{initial} + E_{harvested} - E_{consumed} \quad (11)$$

Where $E_{initial}$ is the initial stored energy, $E_{harvested}$ is the energy derived by solar harvesting, and $E_{consumed}$ is the total energy consumed by both nodes.

A higher residual energy implies that the nodes maintain more energy for continued operation.

In Figure 8, The proposed (SP-WSN) system retains 70% residual energy, compared with 35% for conventional WSN. This demonstrates the benefit of solar energy harvesting and energy-efficient clustering in reducing energy depletion.

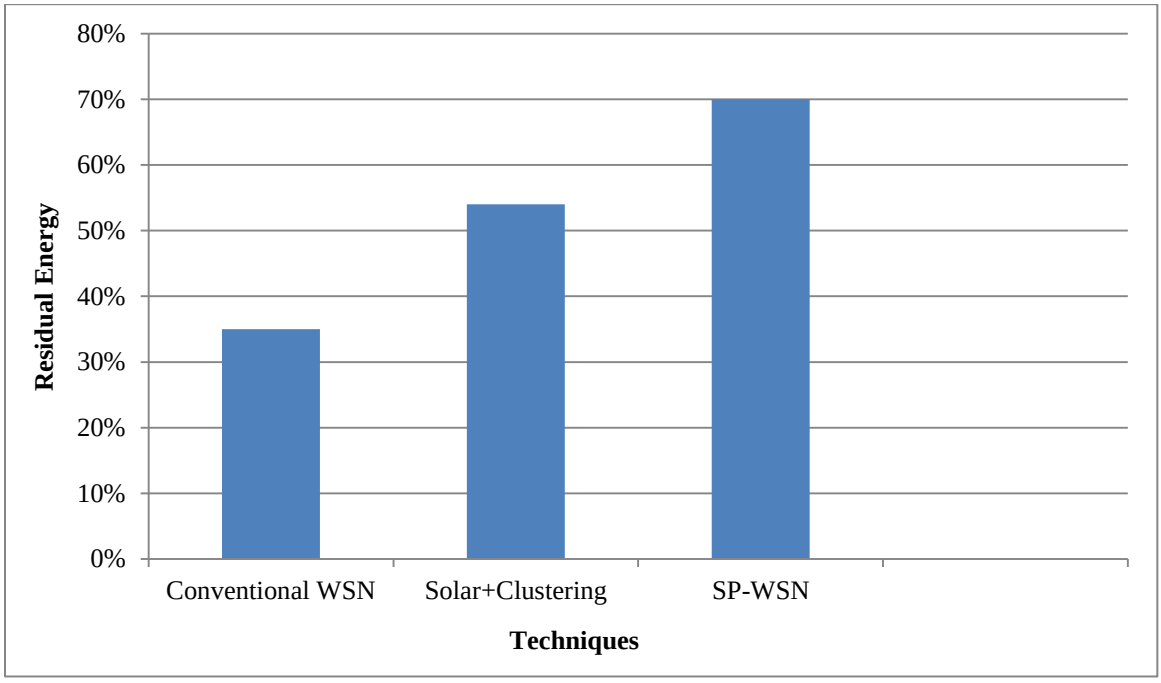


Figure 8. Percentage-based comparison of Residual Energy among three approaches

6. OVERALL RESULTS

The overall analysis examines both energy efficiency and communication performance. Energy consumption and network lifetime indicate the sustainability of the sensor network, while packet delivery ratio and throughout indicate communication reliability and data delivery performance. End-to-end latency and communication range assess how well the LoRa-based communication layer works. The combined research establishes whether LoRa communication, energy-efficient clustering, and solar energy harvesting can offer a dependable and sustainable foundation for long-term smart agriculture monitoring.

7. CONCLUSION

The research develops the Solar-Powered Wireless Sensor Network (SP-WSN) framework for smart farming through the implementation of solar energy harvesting, efficient clustering, and the innovative application of LoRa technology. The framework aims at achieving sustainable agricultural monitoring through powering the sensor nodes with renewable energy, avoiding excessive communication, and facilitating data transfer over long distances. Its performance evaluation is based on measuring energy consumption, network lifetime, packet delivery ratio, communication delay, throughput, and residual energy. The discussed comparison results should be interpreted with the reference to the conditions of experiment/simulation and methods of normalization applied. Future research shall aim at ensuring the framework's validation by deploying it on the field under diverse weather conditions, numbers of nodes, sizes of agricultural fields, and distances of communication.

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