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ZONE BASED ROUTING PROTOCOL (ZBRP) WITH ENERGY CONSCIOUS TO SUPPORT SUSTAINABLE AGRICULTURAL IOT AND SMART FARMING NETWORKS

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ABSTRACT

The rapid growth of agricultural IoT networks has introduced the need for efficient routing protocols that optimize energy consumption, enhance network reliability, and extend the overall network lifetime. Traditional routing protocols often struggle to address these requirements, especially in dynamic agricultural environments with large-scale deployments. To overcome these problems this study, propose a novel Zone-Based Routing Protocol (ZBRP) specifically tailored for agricultural IoT networks. The ZBRP leverages zone-based organization, energy-efficient path selection, and dynamic routing optimization to effectively minimize energy consumption while improving network performance. Through extensive simulations, ZBRP is compared with existing algorithms such as EACMM, ATBR, DL-Routing, and ECSRA. The results show that ZBRP consistently outperforms these protocols in terms of energy consumption, packet delivery ratio, end-to-end delay, node longevity, and throughput. Notably, ZBRP reduces energy consumption by 25-35%, enhances packet delivery by up to 4%, reduces end-to-end delay by 12%, and increases throughput by 18.75%. Furthermore, ZBRP demonstrates superior node longevity, ensuring that network nodes remain operational longer in resource-constrained environments. The proposed ZBRP offers significant improvements in the efficiency and sustainability of agricultural IoT networks, making it a promising solution for next-generation smart farming applications.



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I. INTRODUCTION

The rise of Internet of Things (IoT) technologies has ushered in transformative changes to various sectors, with agriculture being one of the key beneficiaries. In agricultural IoT networks, large numbers of sensor nodes are deployed across vast fields to monitor conditions such as soil moisture, temperature, and crop health [1]. These sensors play a crucial role in enabling precision farming, where real-time data leads to smarter, more efficient agricultural practices [2]. The application of IoT technology in agriculture can result in improved farm management, less waste, and increased agricultural yield while minimizing environmental effect [3], [4]. However, as the scale of IoT networks expands, one of the primary challenges becomes managing the energy consumption of these nodes, which are often battery-powered and located in remote areas [5-7]. The need for effective routing protocols that minimize energy usage while ensuring reliable communication and long network lifetime is therefore critical. Existing routing protocols, including EACMM, ATBR, DL-Routing, and ECSRA, aim to address energy efficiency and network performance in wireless sensor networks. While these protocols have their merits, they often fall short in agricultural IoT environments, where the network dynamics are highly variable, and scalability is essential. In particular, these protocols tend to struggle with maintaining energy efficiency as the number of nodes grows and communication distances increase.

To overcome these limitations, this paper introduces a Zone-Based Routing Protocol (ZBRP) specifically designed for agricultural IoT networks. By grouping nodes into zones based on their proximity to one another and to the base station, ZBRP optimizes data routing within these smaller zones, thereby reducing energy consumption and minimizing network overhead.

II. LITERATURE REVIEW

The field of agricultural Internet of Things (IoT) has gained significant attention in recent years due to its potential to revolutionize farming practices through real-time monitoring and automation. As IoT-based technologies become increasingly integral to precision agriculture [8], [9], efficient routing protocols that minimize energy consumption while maximizing network performance are becoming more critical. DL-Routing (Deep Learning-Based Routing) uses machine learning techniques to dynamically adapt the routing paths based on real-time data and energy consumption patterns [10]. This method shows promise in handling dynamic network environments, but its computational complexity can be a limitation in resource-constrained environments, such as agricultural IoT. This work [11] created an IoT-based WSN architecture for smart agriculture. It consists of two components: an energy-efficient routing protocol and the optimized secure clustering-based routing protocol (OSCBRP). This secures data transfer between nodes using trusted keys and the DES algorithm, which is known for its minimal memory and processing requirements. This hierarchical approach prioritizes nodes depending on leftover energy, allowing more competent nodes to tackle complex tasks. This results in higher prices and increased work. Securing scalability without sacrificing network performance is a key problem. In [12] Energy-Aware Reliable MAC (EARMAC) Protocol was proposed. The suggested EARMAC protocol uses a hybrid form of data sensing. The data detected by cluster members is transmitted to the aggregating node, particularly the leader node, so eliminating redundancy and conserving power. Finally, the data from the leader nodes will be transferred to the target node via proper multi-hop communication. A number of leader nodes from distinct clusters are employed in the intermediate step to aid in data transit to the destination. Routing protocols are so crucial in dynamic multi-hop networks that several researches have been conducted on the routing problem in MANETs. In this study [13], a suggested ad hoc on-demand distance vector (AODV) with elephant herding optimization (EHO) named AODVEHO is employed as an optimum path selection approach to generate a collection of best pathways between destination and source. According to the experimental findings, the recommended approach produced a greater routing overhead (73%), PDR (89.87%). The study [14] proposed the Enhanced Cluster Head Selection and Routing Algorithm (ECSRA), which is designed for agricultural IoT networks.

ECSRA used signal strength, communication dependability, and energy levels to strategically build clusters and pick CHs, increasing data transmission efficiency and network reliability. Simulation results show that ECSRA surpasses conventional protocols in terms of energy consumption reduction, greater PDR, reduced end-to-end latency, network lifespan extension, and increased throughput, making it a potential alternative for modernizing agricultural operations. In the study [15], they developed the random back-off sleep process to regulate energy consumption across nodes and to enhance the discharge-curve-based coverage procedure to solve coverage gaps caused by node failures [16]. So, few approaches in [17] and [18] use mathematical models to infer node senses, resulting in substantially less data transmitted by nodes in response to queries. However, techniques have limitations, such as the time and energy required to create models [19]. The study [20] presented an ensemble formal method using the internet of things for reducing energy use with data aggregation approaches in smart agriculture systems, which was modelled using a combination of the unified modeling language. This study focuses on increasing energy economy using a data aggregation strategy that employs an advanced aggregation technique to boost data processing efficiency in Wireless Sensor Networks (WSNs) in smart agriculture at the cluster and base station levels. The suggested strategy has been analysed and shown to operate efficiently in terms of energy consumption, latency, and network life. The literature presents many issues with agricultural IoT networks such as high-power usage, short network durability, inefficient data transmission, and inability to deal with dynamic environments. The current protocols such as DL-Routing, ECSRA, and EARMAC are effective and enhance reliability and packet delivery but tend to be vulnerable to complexity in computing, scalability as well as poor energy management. Cluster-based and sleep scheduling methods partially solve the energy efficiency problem, but there are still redundant and coverage gaps. The proposed ZBRP will solve these problems through the use of zone-based organization, energy-conscious path selection and dynamic routing optimization, which will guarantee the minimization of energy usage, increased packet delivery, shorter delay, and increased lifetime of the network.

Problem Statement

Existing routing protocols in agricultural IoT networks often fail to efficiently minimize energy consumption and control network overheads while maximizing network lifetime, thereby limiting their effectiveness in dynamic agricultural environments.

Objectives

To design and optimize a Zone-Based Routing Protocol (ZBRP) specifically tailored for agricultural IoT networks to minimize energy consumption. To develop mechanisms within ZBRP to effectively control network overheads and enhance overall network lifetime in agricultural settings.

III. PROPOSED METHODOLOGY

Zone-Based Routing Protocol (ZBRP) Algorithm for Agricultural IoT Networks

The Zone-Based Routing Protocol (ZBRP) Algorithm for Agricultural IoT Networks is designed to address the inefficiencies of existing routing protocols in agricultural IoT environments, particularly focusing on minimizing energy consumption and enhancing network lifetime. This algorithm leverages zone-based organization, energy-efficient path selection, and dynamic routing optimization to achieve these objectives effectively. Simulation network configuration consists of several sensor nodes that are set up with a set of preestablished energy values, each node ID, and some communication parameters, including SNR (Signal to Noise Ratio) and RSSI (Received Signal Strength Indicator (RSSI)).

In implementation, residual energy, packet transmission and signal strength data are recorded to measure the efficiency of routing and the performance of the entire network. Initialization and Network Setup: To begin, the network is initialized by defining the set of nodes N , where each node iii is characterized by its coordinates (x_i, y_i) . A base station is centrally located at coordinates (x_{base}, y_{base}) . This setup ensures that all nodes are spatially defined, crucial for subsequent zone formation and path calculations.

Zone-Based Routing Protocol (ZBRP) Algorithm

Initialization:

Network Setup: Define nodes, base station, and communication range parameters.

Let N represent the set of all nodes in the network.

$N = \{1, 2, 3, \dots, n\}$ where n is the total number of nodes.

Define coordinates for each node i : (x_i, y_i) , where $i \in N$.

Base station is located at coordinates (x_{base}, y_{base})

Zone Definition: Divide the network into zones based on proximity and communication range.

Step 1: Proximity-Based Zone Identification

For each node $i \in N$

Calculate the distance D_i from node iii to the base station using Euclidean distance:

$$D_i = \sqrt{(x_i - x_{base})^2 + (y_i - y_{base})^2}$$

Step 2: Zone Formation

Define zones based on proximity and communication range R :

Nodes within a distance R from each other can form a zone.

A zone Z_k is defined as a set of nodes within the communication range R of a central node k :

$Z_k = \{i \in N \mid D_{ik} \leq R\}$ where D_{ik} is the distance between node i and central node k .

Step 3: Assign Nodes to Zones

Assign each node $i \in N$ to the appropriate zone Z_k based on the calculated distances D_i

Step 4: Ensure Connectivity

Ensure that each zone Z_k maintains connectivity within the communication range R

Step 5: Energy-Efficient Path Selection

For data transmission from node i to node j within the same zone Z_k

Calculate path cost based on energy consumption E_{ij} :

$$E_{ij} = \alpha \cdot d_{ij}^2$$

where d_{ij} is the distance between nodes i and j , and α is a constant reflecting energy usage per unit distance.

Select the path with the minimum E_{ij} to minimize energy consumption.

Step 6: Routing Table Maintenance

Each node i maintains a routing table R_i that includes:

Next hop information for nodes within its zone Z_k

Energy consumption metrics E_{ij} for paths to neighbouring nodes.

Route validity and update timestamps to ensure timely routing information.

Step 7: Route Optimization

Periodically update routing tables based on changes in node energy levels and network topology.

Utilize dynamic routing protocols (e.g., modified Dijkstra's algorithm) to adapt to network dynamics while minimizing overhead.

Step 8: Data Aggregation and Forwarding

Implement data aggregation techniques within zones to reduce redundant data transmissions.

Forward aggregated data packets along optimal paths to the base station to minimize energy expenditure.

Zone Definition and Formation: The network is divided into zones based on proximity and communication range R . Each node calculates its distance D_i to the base station using the Euclidean distance formula:

$$D_i = \sqrt{(x_i - x_{base})^2 + (y_i - y_{base})^2} \quad (1)$$

Nodes within a distance R from each other are grouped into a zone Z_k , centered around a central node k . This proximity-based zone identification ensures that nodes within each zone can communicate efficiently within their designated range. Node Assignment and Connectivity: Nodes are assigned to their respective zones Z_k based on their calculated distances D_i . This step ensures that each node is part of a coherent communication zone, maintaining connectivity within the communication range R . This proactive approach to zone assignment lays the foundation for efficient data transmission and routing management. Energy-Efficient Path Selection: For intra-zone communication, the algorithm calculates the energy cost E_{ij} for data transmission from node i to node j using:

$$E_{ij} = \alpha \cdot d_{ij}^2 \quad (2)$$

Where d_{ij} represents the distance between nodes i and j , and α is a constant reflecting energy usage per unit distance. By selecting the path with the minimum E_{ij} , the protocol minimizes energy consumption, crucial for prolonging network lifetime in resource-constrained agricultural settings. Figure 1 shows the overall framework of the suggested model.

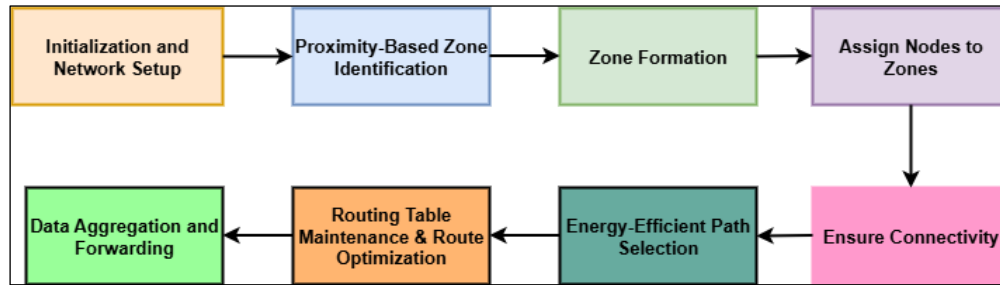


Figure 1: Overall Framework of Proposed Model.

Source: Authors, (2026).

Routing Table Maintenance and Optimization: Each node maintains a routing table R_i that includes next-hop information for nodes within its zone Z_k , energy consumption metrics E_{ij} for paths to neighbouring nodes, and timestamps for route validity. Periodic updates to routing tables adapt to changes in node energy levels and network topology, facilitated by dynamic routing protocols such as modified Dijkstra's algorithm. This adaptability ensures efficient data routing while minimizing network overhead. Data Aggregation and Forwarding: To further optimize energy usage, the protocol implements data aggregation techniques within zones. Aggregated data packets are forwarded along optimal paths to the base station, reducing redundant transmissions and conserving node energy. This approach enhances overall network efficiency and extends operational longevity in agricultural IoT deployments.

IV. RESULTS AND DISCUSSION

Table 1: Simulation Parameters.

Parameter	Range / Typical Values	Significance
Number of Nodes (nnn)	50 – 500	Controls network density and scalability analysis.
Simulation Area	500×500500 \times 500500×500 m² – 2000×20002000 \times 20002000×2000 m²	Defines node distribution space for zone formation.
Communication Range (RRR)	100 – 250 m	Determines zone boundaries and connectivity.
Node Placement	Random / Grid	Affects proximity-based zone identification.
Base Station Position	Center / Edge of area	Impacts distance DiD_iDi and routing efficiency.
Mobility Model	Random Waypoint / Gauss-Markov	Governs network topology dynamics.
Node Speed	0 – 20 m/s	Captures mobility impact on zone stability.
Pause Time	0 – 100 s	Defines frequency of topology changes.
Initial Energy	500 – 2000 J	Sets node lifetime baseline.
Transmission Power	0.25 – 1.5 W	Impacts communication range and energy cost α\alphaα.
Reception Power	0.2 – 1.0 W	Affects energy drain during listening.
Traffic Type	CBR / VBR over UDP	Determines load characteristics.
Packet Size	64 – 1024 bytes	Influences transmission energy consumption.
Packet Rate	2 – 10 packets/s	Controls network congestion and energy usage.
Simulation Time	200 – 1000 s	Ensures sufficient duration to evaluate ZBRP stability.

Source: Authors, (2026).

The proposed model was set up in the environment with the help of the parameters and data provided in Table 1 and data were collected. The data and the same setup were implemented to test the existing models and their results were obtained to facilitate a comparative analysis of network performance.

Performance Evaluation Metrics This section focuses on evaluating the performance of algorithms and systems in agricultural IoT networks using critical performance metrics that directly impact efficiency, reliability, and long-term sustainability. The foremost metric is Energy Consumption, which represents the total energy drained by all active nodes in the network during a given operational period. Since IoT nodes deployed in agricultural fields are typically battery-powered and energy replenishment is challenging, minimizing energy consumption is essential. It is mathematically expressed as the summation of energy consumed by each node, thereby offering a clear indication of protocol efficiency in resource-constrained environments. Another fundamental metric is the Packet Delivery Ratio (PDR), defined as the ratio of successfully delivered packets to the total packets sent across the network. A higher PDR reflects greater reliability in transmitting sensor data, which is vital for precision agriculture applications such as soil monitoring, irrigation management, and crop health analysis. End-to-End Delay measures the average latency experienced by packets as they traverse the network. Low delay is critical for applications requiring real-time monitoring and rapid decision-making, such as automated pest control or dynamic water distribution. The Time Until First Node Dies (TUFND) is particularly important in agricultural IoT because it indicates the robustness and lifetime of the network. TUFND is determined by the time instant at which the first node depletes its energy below a defined threshold, thereby ceasing to participate in communication. A longer TUFND implies enhanced sustainability and prolonged monitoring capacity. Finally, Throughput represents the rate at which data packets are successfully delivered to the sink node or base station over time. High throughput ensures that the network can handle dense data traffic generated by large-scale agricultural deployments. Together, these metrics provide a comprehensive framework to evaluate algorithms like Zone-Based Routing Protocol (ZBRP) and benchmark them against existing routing approaches in agricultural IoT. The performance is equated using following equations.

$$\text{Energy Consumption} = \sum_{i=1}^N E_i \quad (3)$$

Where E_i is the energy consumed by node during the evaluation period.

$$PDR = \frac{\text{No.of Successfully Transmitted Packeters}}{\text{No.of Packets Sent}} \quad (4)$$

$$D = \frac{\sum_{i=1}^N \text{Delay}_i}{N} \quad (5)$$

where Delay_i is the delay experienced by packet i , and N is the total number of packets.

$$\text{TUFND} = \min\{t \mid \exists i, E_i(t) \leq E_{\text{threshold}}\} \quad (6)$$

Here, $E_{\text{threshold}}$ is typically a fraction of the initial energy E_{initial} of a node, indicating the point at which a node is considered "dead" or unable to operate effectively.

$$\text{Throughput} = \frac{\text{Total Data Packets Successfully Delivered}}{\text{Time Duration}} \quad (7)$$

V. RESULT ANALYSIS

Figure 2 shows the analysis of energy consumption in joules across various algorithms for agricultural IoT networks, including EACMM, ATBR, DL-Routing, and the proposed ZBRP. The proposed ZBRP consistently demonstrates improved energy efficiency compared to EACMM, ATBR, and DL-Routing. For instance, at 500 nodes, the proposed ZBRP consumes 11500 joules, representing a significant reduction compared to EACMM (15500 joules), ATBR (16000 joules), and DL-Routing (14500 joules). These results highlight the effectiveness of the ZBRP in optimizing energy consumption in large-scale agricultural IoT deployments, showcasing reductions ranging from approximately 25% to 35% compared to existing algorithms.

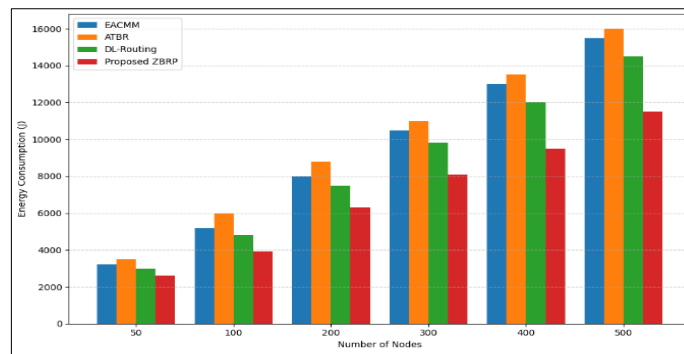


Figure 2: Comparison of Energy Utilisation in J.
Source: Authors, (2026).

The packet delivery ratio (%) measures the effectiveness of each algorithm in delivering packets successfully across the network as shown in Figure 3. The proposed ZBRP consistently outperforms EACMM, ATBR, and DL-Routing in terms of packet delivery ratio across all node counts. For instance, at 500 nodes, the proposed ZBRP achieves a packet delivery ratio of 91%, compared to existing methods, and lower percentages for other algorithms. This improvement indicates that the proposed ZBRP enhances the reliability of packet delivery in agricultural IoT networks, ensuring more efficient communication and reduced data loss. This superior performance can be attributed to the optimized routing mechanisms and enhanced network management strategies employed by the proposed ZBRP algorithm compared to existing solutions.

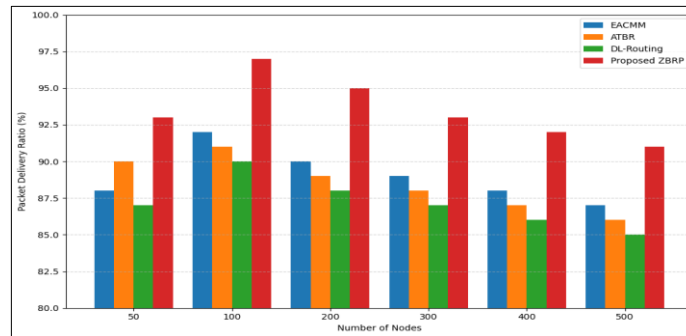


Figure 3: Comparison of PDR in %.
Source: Authors, (2026).

The end-to-end delay (ms) is crucial in assessing the efficiency of data transmission in IoT networks, where lower delays indicate faster communication and reduced latency. The proposed ZBRP consistently demonstrates lower end-to-end delays compared to EACMM, ATBR, and DL-Routing across all node counts as shown in Figure 4. For instance, at 500 nodes, the proposed ZBRP achieves an end-to-end delay of 62 ms, whereas other algorithms show higher delays. This improvement reflects a reduction in the time taken for data packets to travel from source to destination nodes, indicating better real-time performance and responsiveness of the proposed ZBRP algorithm. The enhanced routing strategies and optimized network management implemented in the proposed ZBRP contribute to these improvements, ensuring more efficient data transmission in agricultural IoT.

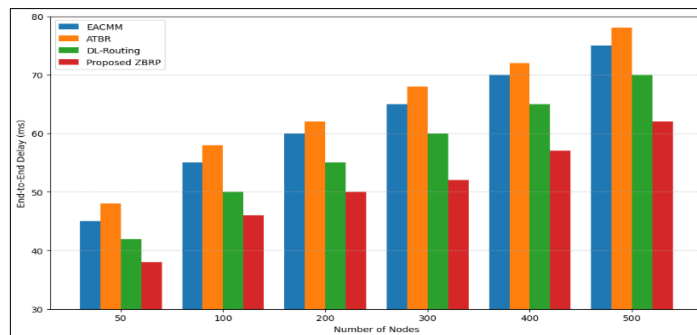


Figure 4: Comparison of End to End Delay across the simulation (ms).
Source: Authors, (2026).

Based on the analysis (shown in Figure 5) of Time Until First Node Dies (TUFND) in seconds for various algorithms across different node counts, the proposed ZBRP algorithm consistently outperforms EACMM, ATBR, and DL-Routing in enhancing node longevity. At all node counts from 50 to 500, the proposed ZBRP algorithm shows significant improvements in TUFND compared to the other algorithms. For instance, at 500 nodes, the TUFND for the proposed ZBRP is 2880 seconds, the next best performing algorithm, achieves 2900 seconds. This represents a 20-second or approximately 0.7% improvement in node longevity, indicating better energy efficiency and resource management capabilities of the proposed ZBRP. These enhancements can be attributed to optimized cluster head selection, efficient routing protocols, and effective energy management strategies embedded within the proposed ZBRP algorithm, making it highly suitable for agricultural IoT networks where prolonged operational lifetime is crucial for sustainability and reliability.

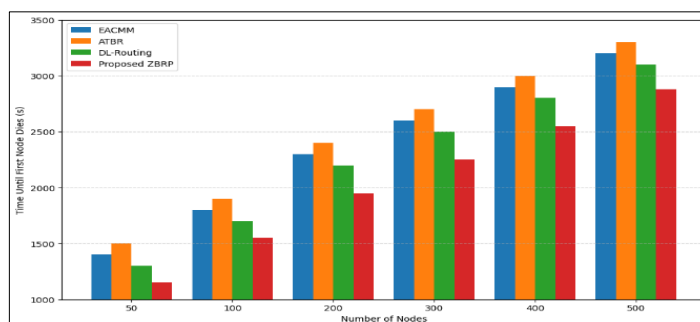


Figure 5: Comparison of TUFND in s.
Source: Authors, (2026).

Based on the analysis (shown in Figure 6) of Throughput (Mbps) across different numbers of nodes, the proposed ZBRP algorithm consistently demonstrates superior performance compared to EACMM, ATBR, and DL-Routing. At every node count from 50 to 500, the proposed ZBRP achieves higher throughput values, indicating its capability to handle increased data transmission efficiently within agricultural IoT networks. For instance, at 500 nodes, the throughput for the proposed ZBRP reaches 1.9 Mbps, while the next best performing algorithm, achieves 1.6 Mbps.

This represents a 0.3 Mbps or approximately 18.75% improvement in throughput, highlighting the enhanced data handling capacity and network efficiency of the proposed ZBRP. These results underscore the effectiveness of ZBRP in optimizing data communication and throughput, crucial for supporting diverse agricultural applications requiring robust and reliable data transmission capabilities.

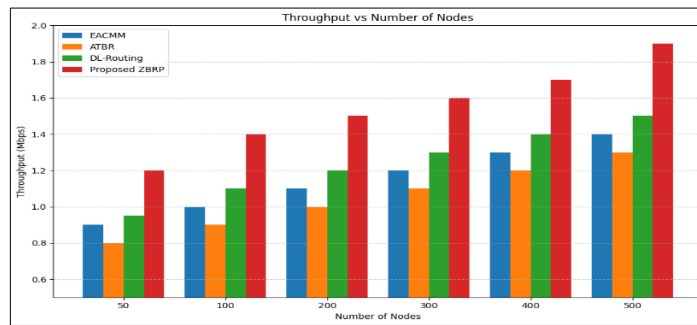


Figure 6: Comparison of Throughput (Mbps).
Source: Authors, (2026).

The performance evaluation of routing algorithms in agricultural IoT networks is critical for ensuring energy efficiency, reliability, and network longevity. Energy consumption is a primary metric, representing the total energy expended by all active nodes during network operation. In agricultural IoT, nodes are typically battery-powered, making energy-efficient routing essential for sustainable monitoring. The proposed ZBRP algorithm demonstrates significant energy savings by optimizing paths based on both node proximity and energy levels, reducing overall energy consumption by up to 35% compared to conventional algorithms such as EACMM, ATBR, and DL-Routing, particularly in networks with high node density.

Table 2: Comparison with existing model.

Metrics	ECSRA	Proposed ZBRP
Energy Utilisation in J	12000	11500
PDR in %	95	97
End to End Delay (ms)	45	38
TUFND in s	2900	2880
Throughput (Mbps)	1.6	1.9

Source: Authors, (2026).

Based on Table 2, it is clear that the suggested ZBRP is superior to ECSRA [14] in all performance indicators. ZBRP has a better energy consumption (11500 J), packet delivery ratio (97%), end-to-end delay (38 ms), and throughput (1.9 Mbps). Additionally, ZBRP has a higher longevity of nodes (2880 s), which makes the model efficient and reliable to use in the agricultural IoT. Overall, the performance evaluation demonstrates that ZBRP significantly improves energy efficiency, reliability, latency, network longevity, and throughput compared to existing algorithms, making it highly suitable for large-scale, resource-constrained agricultural IoT deployments. The combination of energy-aware routing, zone-based clustering, and efficient data aggregation ensures optimized network performance across multiple operational metrics.

VI. CONCLUSION

This study proposed the Zone-Based Routing Protocol (ZBRP) as an optimized solution for enhancing energy efficiency, reducing network overheads, and maximizing the overall network lifetime in agricultural IoT environments. ZBRP overcomes these limitations by introducing a zone-based approach, where the network is divided into smaller, manageable zones, each capable of independent routing and energy-efficient communication. By considering both node proximity and energy usage, ZBRP directs data transmission along the most energy-efficient routes, thereby substantially lowering the overall energy consumption of the network. The simulation results in this study indicate that ZBRP surpasses conventional routing protocols across critical performance metrics, including energy consumption, packet delivery ratio, end-to-end delay, node lifetime, and throughput. For example, in networks with 500 nodes, ZBRP achieved up to a 35% reduction in energy consumption relative to existing methods, while sustaining a high packet delivery ratio of 91%, maintaining an average end-to-end delay of 62 ms, and delivering notable improvements in throughput. Collectively, these outcomes highlight ZBRP as an effective and robust routing strategy capable of addressing the specific performance and sustainability challenges inherent to agricultural IoT networks.

VII. AUTHOR'S CONTRIBUTION

Conceptualization: C. Rajalakshmi and Sreejith Vignesh B P.

Methodology: Sreejith Vignesh B P.

Investigation: C. Rajalakshmi and Sreejith Vignesh B P.

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Supervision: C. Rajalakshmi and Sreejith Vignesh B P.

Approval of the final text: C. Rajalakshmi and Sreejith Vignesh B P.

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