International Journal of Innovative Research and Scientific Studies, 8(4) 2025, pages: 1250-1259

IJIRSS
International Journal of Innovative Research & Scientific Studies

ISSN: 2617-6548

URL: www.ijirss.com

A review of energy-efficient clustering and routing techniques in wireless sensor networks: Key metrics and future trend

Yazeed Alsarhan[1*], Nidal Turab[2] Hasan Abualese[3] Hamza Abu Owida[4]

[1,2,3]*Faculty of Information Technology, Al-Ahliyya Amman University, Amman, Jordan.*
[4]*Faculty of Engineering, Al-Ahliyya Amman University, Amman, Jordan.*

Corresponding author: Yazeed Alsarhan (*Email: y.alsarhan@ammanu.edu.jo*)

Abstract

Wireless Sensor Networks (WSNs) have become a cornerstone of modern technology, especially in applications like the Internet of Things (IoT), where they provide scalable and effective solutions for communication and monitoring applications. However, the finite energy of sensor nodes introduces a significant challenge, as it directly influences the network's lifespan and reliability. Routing protocols and clustering solutions have emerged as ideal ways to address these energy concerns. By forming sensors into clusters and enhancing data transmission routes, these protocols reduce energy consumption and improve network efficiency. Modern approaches incorporate techniques such as metaheuristics, fuzzy logic, and machine learning to address issues like load balancing, node mobility, and network topology changes. Despite considerable progress, gaps remain in scalability, Quality of Service (QoS) integration, and the adaptability of clustering protocols for dynamic environments. This research reviews the state of the art in optimizing energy efficiency in Wireless Sensor Networks. It addresses routing approaches and clustering solutions and highlights performance and quality key metrics and future trends.

Keywords: Artificial intelligence, Clustering, Quality of service, Internet of things, Wireless sensor network.

DOI: 10.53894/ijirss.v8i4.8053
Funding: This work is supported by Al-Ahliyya Amman University, Jordan.
History: Received: 28 April 2025 / **Revised:** 30 May 2025 / **Accepted:** 3 June 2025 / **Published:** 24 June 2025

Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.
Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.
Publisher: Innovative Research Publishing

1. Introduction

The Internet of Things continues to play a key role by linking various technologies such as cameras, actuators, vehicles, and sensors into integrated systems [1]. The widespread deployment of IoT sensor networks has reshaped how we interact with our surroundings by enabling seamless device connectivity and large-scale data acquisition [2]. Within Wireless Sensor Networks (WSNs), clustering techniques are widely employed due to their ability to reduce routing delays, conserve energy, and efficiently manage large data loads. Key characteristics of clustering include inter-cluster communication, the number of clusters, cluster size, cluster density, message count, and network stability [3]. Figure 1 illustrates the essential elements of clustering in WSNs along with various communication models [4]. Four main types classify routing protocols in WSN: reliable routing, topology-based, communication model, and network structure. Each category is further subdivided into specific subgroups, as shown in Figure 2 [5].

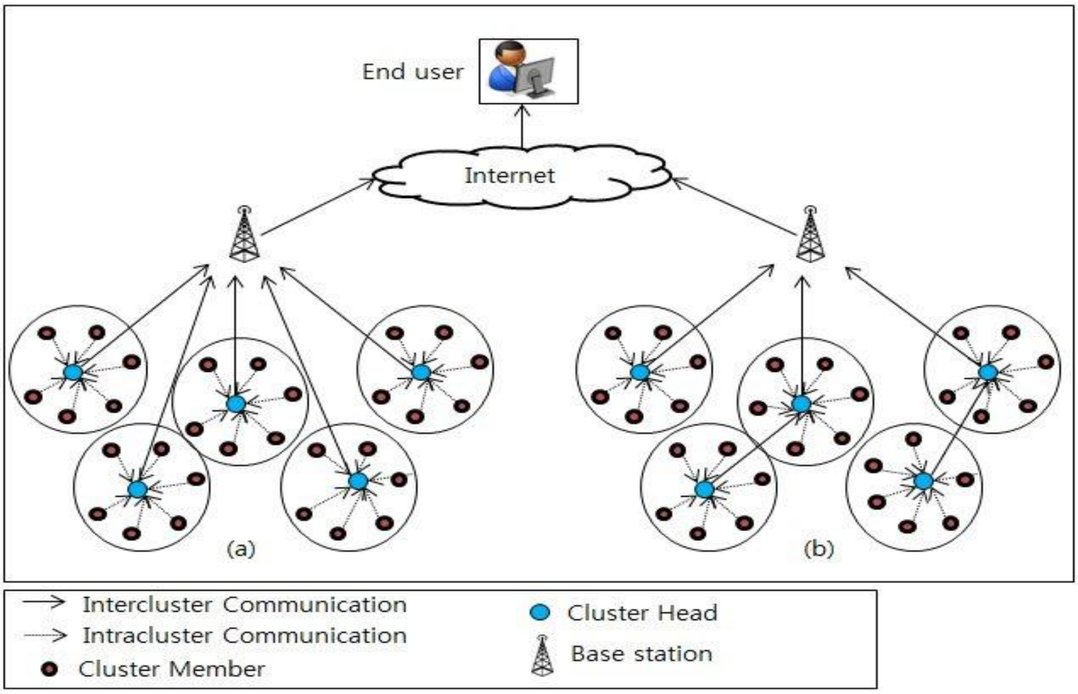

Figure 1.
Key elements of the Clustering-based approach in WSN, (a) communication style based on single-hop and (b) communication style based on multi-hop.

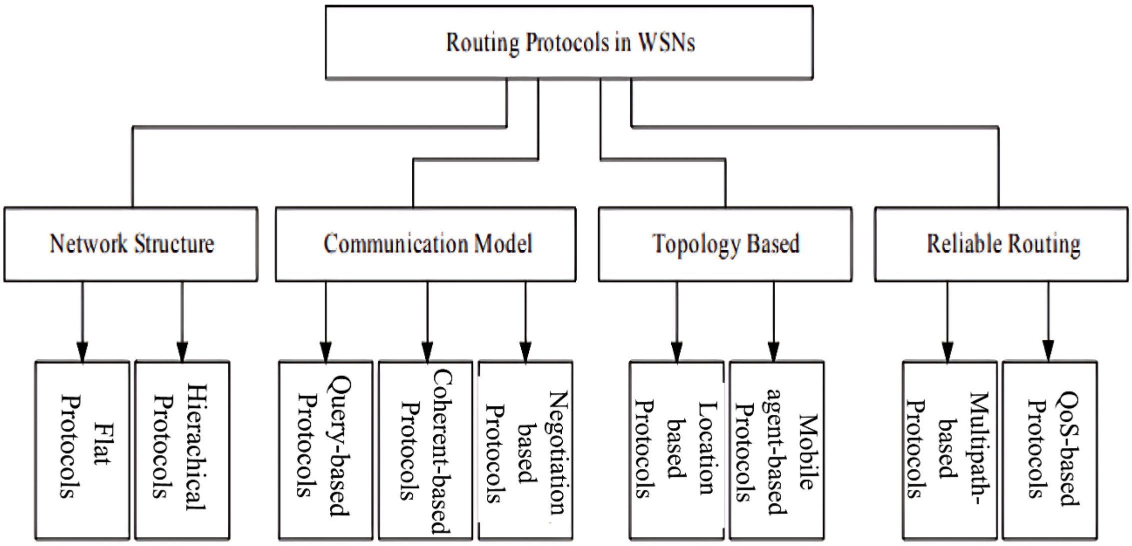

Figure 2.
Categorization of Routing Protocols in WSNs.

2. Literature Review

Meenakshi and colleagues in Meenakshi et al. [6] extended the network lifespan through optimized clustering and routing strategies. For clustering, they employ the Meta-Inspired Hawks Fragment Optimization (MIHFO) algorithm, with passive clustering for selecting cluster heads. While for routing, they used the Heuristic Wing Antfly Optimization (HWAFO) algorithm to find optimal paths. Criteria such as distance, node degree, residual energy, and centrality were used for both cluster head choice and routing efficiency. Five primary key metrics are considered: total energy consumption, active nodes, data packet delivery, throughput, and packet delivery ratio. The results proved that the proposed approach outperforms Butterfly Optimization Algorithm (BOA)/Ant Colony Optimization (AC), Distribute Energy-Efficient Clustering (DEEC), and Low-energy Adaptive Clustering Hierarchy (LEACH) with respect to stability, network reliability, and energy efficiency.

Hu et al. [7] developed routing and clustering techniques, Quantum Particle Swarm Optimization with fuzzy logic (QPSOFL). For clustering, enhanced QPSO includes Sobol sequences for population diversification, along with Gaussian perturbations and Lévy flights for position updates. For routing, fuzzy logic was adopted to select the ideal next-hop cluster head according to energy deviation, residual energy, and relay distance. The performance was then compared with other techniques such as clustering and routing approaches based on fuzzy logic and PSO (FLPSOC), a fuzzy-based improved Harris's Hawk Optimization Algorithm (IHHO-F), enhanced fuzzy inequality clustering and routing protocols (E-FUCA), and fuzzy Grey Wolf Optimization (F-GWO). The considered criteria are energy consumption, throughput, and network lifetime for routing and clustering efficiency.

Saemi and Goodarzian [8] proposed a routing protocol associated with optimizing key aspects such as speed and energy efficiency. Both the local search algorithm (LSA) and the global search algorithm (GSA) were combined for efficient pathfinding. The outcome of that combination is known as the Hybrid Metaheuristic Algorithm (GSLS). A parallel search mechanism was adopted by LSA and GSA to find the best paths through the simultaneous exploration of the problem space.

Raji and Taofeek-Ibrahim [9] proposed a cross-layer based opportunistic routing protocol. (CORP), Energy-efficient routing based on combinatorial random sampling bat optimization (ERFN-CSSBO) protocols and fuzzy neural networks to optimize path selection. On the other hand, for cluster head selection, K-Medoid clustering was used, which is associated with energy state, node position, and proximity. Thus, optimal cluster head selection can be achieved through the Harmony Search Algorithm (HAS) and the Hybrid BFO algorithms. Selecting the best routing path by multiple factors such as connection stability, energy, distance, and trust. Different network efficiency metrics were evaluated, such as packet forwarding rate, network lifetime, throughput, delay, energy consumption, and packet loss rate. Results show improved QoS and the performance of the network.

The research by Ketshabetswe et al. [10] aimed to enhance WSN energy efficiency and improve optimal path discovery by integrating data compression and outlier detection techniques. Two techniques were considered: a data compression algorithm and path optimization. The former was associated with the Fast and Efficient Lossless Adaptive Compression Scheme with Outlier Detection and Replacement (FELACS-ODR) schema. Meanwhile, the latter involved combining FELACS-ODR with compressive sensing (CS). Two main metrics were studied: path length reduction and energy consumption trends. Results showed improvements in WSN energy efficiency, and energy consumption increased slowly with compression.

Sharada et al. [11] proposed a technique to find the ideal cluster count and enhance multi-user clustered communication. Two areas were involved: clustering/sensing and optimization. Adaptive algorithm, adaptive ant colony distributed intelligent-based clustering algorithm (AACDIC), is used for selecting the optimal cluster count. The technique was based on distributed and connectedness cluster-based sensing. For optimization, multi-user communication was adopted to reduce power usage and enhance the convergence rate. Five main metrics are considered: signal-to-noise ratio (SNR), secondary users' average power reduction, node power usage reduction, false positive rate, and probability of detection. The results showed significant improvement in dynamic environmental conditions and optimized network capacity performance.

Gopalan et al. [12] aimed to optimize cluster head selection, reduce latency, and improve energy efficiency for WSN. For clustering optimization, the Bacterial Foraging Optimization with Harmony Search Algorithm (BFO-HAS) is used. Meanwhile, the CORP protocol was used for routing. The CORP is implemented to reduce network overhead and determine the fastest route. The results were then discussed according to quality and network efficiency metrics such as QoS, packet loss rate, power consumption, throughput, Packet Delivery Ratio (PDR), packet latency, and network lifespan.

The research by Pal et al. [13] used a multi-objective binary GWO algorithm for selecting the optimal clustering centers. The study aimed to maximize the distance among Cluster Heads (CHs) and their overall energy. In addition, it sought to minimize the compactness, their number, and the energy used for non-CH to CH transmission. Four main performance metrics were studied: cluster head count, stability period, residual energy, and network lifetime. The developed method is compared with the evolutionary routing protocol (ERP), stable election protocol (SEP), Bee-inspired Energy-efficient Clustering Protocol (BEECP), and intelligent hierarchical clustering and routing protocol (IHCR) protocols.

An energy-efficient routing solution proposed by Ali et al. [14]. The proposed routing protocol aimed to extend network lifetime and minimize energy consumption. The performance was evaluated against other similar protocols, such as Cluster Head Election using Fuzzy Logic (CHEF), Dynamic Fuzzy Logic Clustering (DFLC), Energy-Aware Clustering Protocol in Fuzzy Logic (ECPF), LEACH, Gupta's protocol, and Unequal Cluster-Based Routing (UCR) protocols. Four main metrics for the proposed protocols were considered: end-to-end delay, drop rate of alive sensor nodes, packet loss rate, and energy consumption. Results indicated the robustness of the proposed solution under various network conditions, such as packet loss and lower energy consumption metrics.

Janarthanan and Srinivasan [15] introduced a multi-objective, energy-aware routing approach. The aim was to boost WSN performance. Their research is associated with enhancing data transmission and cluster head selection within sensor networks. An Aggregated Graph Neural Network (AGNN) is used for choosing the optimal cluster head. Meanwhile, for selecting a route with minimal latency, Hybrid Bee Colony Multi-Objective Optimization- Border Collie Optimization (BCMO-BCO) is employed. Moreover, trust path techniques were adopted for secure data transmission. A comparison in performance was conducted against other related protocols, such as Self-attention based- Progressive Generative Adversarial Network- data aggregation in WSN (SA-PGAN-DAWSN), MDAS-DAWSN, and Taylor-spotted hyena optimization for dependable and energy-efficient CH selection-based safe data routing and fault tolerance in WSN (T-SHO-DAWSN). The results indicate a remarkable reduction in delays and an enhancement in both network lifetime and packet delivery ratio.

Surenther et al. [16] developed the Machine Learning-based Energy Optimization Approach (ML-EOA). The approach aimed to increase data reliability, network coverage, and energy efficiency. For data aggregation, the proposed method integrates data aggregation techniques to streamline data processing. Artificial neural network (ANN) is utilized for cluster head selection with efficient energy distribution. In addition, a fuzzy logic-based approach was used to enhance sleep cycles to prolong network lifetime. The study improved network metrics such as network lifespan and coverage. Moreover, high data delivery ratio, lower latency, and lower energy consumption were achieved.

The research by Raj and Duraipandian [17] aimed to enhance both energy efficiency and network performance in WSN. It addressed enhancing cluster heads selection by integrating two optimization techniques: HSA and Bacterial Foraging Optimization (BFO) algorithms. The associated algorithms focused on the distance between nodes and on reducing energy consumption. QoS parameters were considered: packet loss rate, throughput, and packet forwarding rate. Furthermore, other metrics include end-to-end delay, energy consumption, and network lifetime. Results showed a remarkable improvement in network lifetime, particularly for crucial applications that required reliable data transmission.

Tolani et al. [18] introduced the deviation-aware adaptive bit-mapping medium access control protocol (DAABMA). They aimed to improve energy efficiency in WSN. The developed protocol provided a technique to reduce energy consumption, particularly for resource-constrained environments where efficient energy management was important. The results showed significant energy savings compared to existing protocols such as Adaptive Bitmap Aided (ABMA) and Energy-Efficient Bitmap Aided (EBMA) protocols.

The research by Salman et al. [19] is associated with enhancing clustering technology within WSNs. The research aimed to develop a protocol able to improve cluster head selection, cluster formation, and data transfer processes. Four key aspects were adopted to boost clustering techniques as follows: selecting the ideal number of cluster heads, cluster formation based on distance, and nominating the optimal main and secondary heads. The developed protocol employed two different data scheduling techniques: Time Division Multiple Access (TDMA) and Carrier Sense Multiple Access (CSMA). The former relates to scheduling data transfer within clusters, whereas the latter is associated with the base station for managing its inter-cluster data transmission. The results were compared against two protocols, LEACH and SEP. The developed method demonstrates its efficiency in network lifetime and throughput metrics.

Somula et al. [20] developed an Osprey optimization algorithm based on efficient cluster head selection (SWARAM). An energy-efficient optimization algorithm, the developed method is associated with the IoT paradigm. It is based on selecting a cluster head in WSN. Two-phase approaches were employed: cluster head selection and cluster formation. The performance metrics adopted were PDR and network lifetime. The results proved a significant improvement in both metrics against other algorithms, such as artificial rabbits' optimization-based energy-efficient algorithm (EECHS-ARO), HSWO, and improved grey wolf optimization algorithm-based energy-efficient (EECHIGWO).

Almuzaini et al. [21] proposed Cluster Energy Hop-Based Dynamic Route Selection (CEH-DRS) as a routing solution. The aim was to optimize the service in mobile WSN and maintain the shortest path criteria. Both Cluster-based fuzzy and bee colony route optimization models are employed. The developed method enhances the following key metrics: routing overhead, detection accuracy, throughput, end-to-end delay, and time complexity. Furthermore, the protocol adopted other metrics for evaluating mobility performance, such as Received Signal Strength Indicator (RSSI), Link Loss Rate and Expected Transmission Count (ETX).

Babatunde et al. [22] developed an energy-efficient solution for sensor nodes called Greentooth. The protocol overcomes power outages and outage-induced timing inaccuracies by deploying a dual-radio design and TDMA-style communication scheduling. The research is associated with two main metrics: receiver lifetime and throughput. The throughput shows a significant improvement, especially compared with asynchronous wake-up on demand, Multiple Access Control (AWD MAC), and Receiver-Initiated consecutive packet transmission wake-up radios (RI-CPT-WuR).

A cluster-based protocol was proposed by Rizky et al. [23]. The proposed protocol splits the network into multiple channels, with each channel containing a cluster head. The study adopted a multi-channel hierarchical technique based on clustering. Additionally, to incorporate odd-even scheduling, a throughput metric is included to measure the protocol's performance. It showed remarkable results in throughput due to the fact that not all nodes are active.

A routing protocol for sensors within IoT was proposed by Suresh et al. [24]. It was implemented by Federated Deep Reinforcement Learning (FDRL) to provide an intelligent data routing strategy. Key challenges were errors based on node selection, packet loss, computing complexity in data routing, and frequent node relocation. Enhancing the routing decisions is achieved through several key metrics such as communication delay, time complexity, message overhead, energy efficiency, and data sum rate. The results are compared to existing routing protocols, including deep reinforcement learning-based multi-optimality routing (RLR-M), Decentralized Partially Observable Markov Decision Process (Dec-POMDP), Cooperative Deep Reinforcement Learning (CDRL), and Multi-hop State-Aware Traffic Flow Forecasting (MHSA-TFF). The contributions include improvements in packet delivery rates, data delivery reliability, sum rate, throughput, network capacity, and **reduction** in energy consumption.

The Power Optimization and Hybrid Data Aggregation (POHDA) approach was developed by Al-Heeti et al. [25]. A hybrid data aggregation was used for selecting an effective cluster head. Key parameters are adopted for choosing as follows: latency, threshold value of the node, mobility, and distance. As a result, the communication overhead, residual energy, end-to-end delay, and energy consumption are minimized in the network. The results are compared with current methods, e.g., Adaptive Fuzzy Clustering Algorithm (APCC-WSN), HCCS-WSN, and FMCA-WSN. Accordingly, the proposed method achieved better performance in the criteria, including packet delivery ratio and energy efficiency.

A novel framework developed by Sahoo et al. [26] targeted WSNs in uncertain environments. The framework aims to prolong WSN lifetime by combining intelligent clustering algorithms and multi-criteria decision-making (MCDM). The developed approach shows enhancement in energy efficiency compared to LEACH with Fuzzy Clustering, Residual Energy-Aware Clustering with Isolated Nodes (REAC-IN), and hybrid energy-efficient distributed (HEED).

The study proposed by GANGAL in Gangal et al. [27] aimed at integrating the analytic hierarchy process (AHP) with the LEACH algorithm. The research considered a matrix of values within nodes, containing all possible values for cluster head selection. The criteria were associated with both distance and energy relative to the sink. A weighted approach was assigned from 1 to 9 for evaluation. The results demonstrated an enhancement in network lifetime while maintaining a high number of packets transmitted to the sink.

The research developed by Preetha et al. [28] provided a technique for cluster formation and head selection. That technique involved using War Strategy (WS). A fault-tolerant technique relying on Contextual Attention Greylag Goose Network (CAGGN) is employed to enhance network survivability. Whereas, selecting the optimum WSN route is done based on Leopard Seal Optimization (LSO). Seven main measures are studied through these techniques as follows: survivability, packet delivery ratio, throughput, energy consumption, computing time, network lifetime, and latency. These techniques show a significant enhancement in the network, particularly in the average energy consumption rate and throughput.

A technique proposed by Lee [29] aimed to prolong WSN lifetime. The developed technique reduced the distance between the communicating sensor nodes and their cluster heads. This, in turn, formed a group of clusters on a two-dimensional plane. Two main groups were considered: the member nodes group and the cluster nodes group. Member nodes were selected based on the shortest communication distance, while cluster nodes were grouped based on adjacent nodes with closer distances from each other. Results demonstrate significant improvement in terms of cluster uniformity within short distances.

Liu et al. [30] presented an algorithm to minimize the average transmission time for nodes within cluster formation. That algorithm is associated with low-delay data transmission, LEACH-D and IoT approaches to improve their efficiency. Evaluating the performance can be done with the assistance of the average transmission time metric. The results showed a remarkable improvement in both average transmission time and FND.

A routing mechanism was developed by Fernandes et al. [31] for WSN operating underwater. Aimed to provide efficient and reliable communication for water quality monitoring applications. The fitness function could be computed using the CS algorithm, based on key metrics such as loss ratio, depth value, and energy usage. Thus, the optimal next hop can be selected efficiently. Accordingly, results demonstrated an improvement in both residual energy and packet forward ratio.

A routing protocol for WSN, namely the fault-tolerant multipath routing protocol (MRP-FT), was proposed by Kaur [32]. The key objective of the developed protocol was to improve reliability and energy efficiency. The results were compared to the LEACH protocol. The implementation of the proposed protocol showed improvements in the following metrics: decreased energy consumption, reduced packet overhead, lower delay, and increased reliability.

Equation-based analysis and mathematical modelling were developed by Gupta and Yadav [33]. It was associated with WSN in remote locations with limited resources. It aimed to enhance ILEACH's performance and provide solutions through probability distributions and equations. These could control the behavior of sensor nodes, their lifetime, and energy consumption. A comparison was conducted between LEACH and Improved LEACH (ILEACH). The results showed better performance in areas such as data throughput, network lifetime, and energy efficiency.

A scheduling algorithm with an energy-saving strategy was presented by Ma et al. [34]. It targets wireless sensors that are deployed for monitoring gas and oil pipelines. The approach was developed under transform networks and aimed to improve data transmission efficiency and energy consumption. Both environmental variations and energy consumption patterns can be used to predict the energy consumption of data transmission.

A Geographic Forwarding Energy Efficient Routing Protocol (GF-EERP) for WSNs is presented by Bairagi et al. in [35]. The proposed solution overcomes the limitations of the existing Geographic Energy Aware Routing protocol (GEAR). It provides several strategies, such as categorizing nodes into groups based on their energy, region head selection by specific standards, and removing dead nodes through communication and multi-hop communication. The main parameters used for evaluation are Network Throughput, Network Delay, and Data Delivery Ratio. As a result, region head selection and distinctive node categorization demonstrate a robust strategy compared to other strategies such as GEAR, M-GEAR, Greedy Perimeter Stateless Routing (GPSR), and Geographic Adaptive Fidelity (GAF).

The deficiency of convergence in the LEACH protocol was overcome by the research presented by Klidbary & Javadian in Haghzad [36]. They proposed a combinational strategy including a novel objective function and a genetic algorithm (GA). These methods integrated distance and energy levels. Another significant aspect is representing cluster heads and the ease of cluster node selection by using chromosomes. As a result, clustering is performed dynamically by iteratively and is able to specify dead nodes. The approach improves both network lifetime and the quality of clustering. The results demonstrated the effectiveness of the developed method, compared to other approaches, including LEACH, LEACH_EX, and LEACH_E.

Other work associated with the enhancement of WSN durability and life span was introduced by Vhatkar et al. [37]. In their research, a novel adaptive routing protocol called M-PDCH is proposed. Unlike PEGASIS with Double Cluster Head (PDCH) protocol, this adaptive protocol offers an alternative solution to address the high packet drop issue. Additionally, results indicate that both delay and energy consumption are minimized compared to the PDCH protocol.

The energy waste in WSN was investigated by Majid Lateef and Al-Qurabat [38]. For network clustering, the research adopts the K-means method. While computing the optimal number of clusters, the silhouette approach is considered. Additionally, to minimize network energy usage, the study focuses on distributing the load across nodes. This can be done by selecting a cluster head according to AHP and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The implemented technique indicates an increase in network lifetime compared to Energy-Saving Clustering Algorithm (ESCA), improved grid-based hybrid network deployment (IGHND), and Multi-Objective Fuzzy Clustering Method (MOFCA).

The framework by Pathak & Yadav focuses on WSN energy in Pathak and Yadav [39]. That research presented an extension of the Distributed Energy-Aware MAC (DE-MAC). The methodology adopted relates to identifying low-energy nodes. Consequently, these nodes are assigned less time for broadcasting and more time for sleeping. NS2 is used in this research for evaluation purposes against DE-MAC. The analysis conducted validates the efficiency of the approach, primarily in terms of performance factors such as packet delivery ratio, throughput, and residual energy.

A clustering-based routing protocol was introduced by Jing [40]. That protocol was designed for WSNs aiming to extend their lifetime. It addressed the problems arising from frequent cluster maintenance and unnecessary message overhead used for cluster creation. The study introduced Harris Hawks Optimization Clustering with Fuzzy Routing (HHOCFR). The Harris Hawks method is employed to select the ideal cluster heads.

A routing protocol for WSN was introduced by Raji and Taofeek-Ibrahim [9]. The proposed method combines multiple techniques, including LEACH, the Chinese Remainder Theorem (CRT), and artificial intelligence (AI). The protocol aims to enhance network lifetime and efficiency. The performance of the developed method is evaluated based on network longevity, energy efficiency, data delivery ratios, and latency. The research is compared against existing approaches such as MRHC-LEACH, CRT-LEACH, and Power Efficient Gathering in Sensor Information Systems (PEGASIS).

A low-energy WSN routing protocol based on a security-aware technique was presented by Shen and Xu [41]. Two phases were considered: the route establishment phase and fault tolerance/data privacy. The former was achieved by a grey clustering algorithm. It performs a security analysis of the cluster area and categorizes its security status. The latter phase used a dynamic slicing approach. It is related to the distance between cluster heads and the security status of the nominated clusters.

A route selection model for WSN was proposed by Shah and Afzal [42]. The main objective of the proposed research was to improve the efficiency of node energy. An evolutionary theory-based game was used for this purpose. Both the distance to the next hop and the residual energy were the evaluation factors used for nodes. Distances to the next hop are determined for both opportunistic and optimal routing scenarios. Thus, the ideal transmission route can be computed in the matrix.

An intrusion protection approach for WSN was developed by Dubey [43]. The research presented an Energy-Efficient and Secure Routing (ESR) protocol. It overcame high network load and malicious nodes, which caused re-transmissions and a high number of route discovery issues. Thus, the developed approach distributes energy consumption and enhances the process of cluster head selection. The model utilized segment tables to perform inspections in nodes to discover any malicious activities.

A cluster-based approach was introduced by Hada and Srivastava [44]. The approach aimed to extend WSN lifetime by using clustering, where the cluster head handled routing data. The research highlighted the importance of choosing both clustering algorithms and hyperparameters that control cluster head selection.

A set of algorithms developed to ensure WSN energy efficiency by Gül [45]. These sets aim to provide path planning with energy efficiency, be able to collect sensor data with minimum energy, extend network lifetime, and increase sensor connectivity. The research introduced a modified Nearest Neighbor-based method to apply certain constraints for specific undesirable routes.

A framework that enhanced the LEACH protocol was proposed by Sridevi and Prakash [46]. The framework is referred to as the load-aware active LEACH protocol (LAALEACH). It focused on WSN within an IoT environment. The main goal of the framework was to apply load-aware active routing. The three main modules are load-aware active routing, load pattern tracker, and rapid load estimator. The performance parameters used in this work are energy consumption, packet delivery rate, throughput, and communication delays.

Energy-efficient cross-layer was introduced for WSN by Sivaraman and Leburu [47]. The research addressed sustaining QoS metrics while prolonging the network lifetime. Three techniques were adopted to improve performance: fuzzy k-medoids (FKMeds) clustering, the hybrid improved grey wolf and ant colony (HIGWAC) optimization, and the adaptive ranking-based energy-efficient opportunistic (ARanEOR) protocol. The first is used to assemble sensor nodes and to enhance scalability, resilience, and reduce network traffic. The second relates to cluster head selection, optimizing energy stability, minimizing distances, and reducing latency. The third is responsible for data transmission via the shortest route. The method showed significant contributions to latency, network lifetime, and energy.

A routing protocol associated with distributing the energy evenly was developed by Suman et al. [48]. The protocol replaced nodes with lower energy with higher energy nodes. Two techniques were used: the data fusion technique and the genetically updated algorithm. The research contributes to minimizing data transmission and enhancing overall energy efficiency. Results were compared in terms of packet loss ratio, packet delivery ratio, and energy usage.

A developed routing scheme that takes advantage of the privileges of chain communication was proposed by Ramezanzadeh and Shokrzadeh [49]. That scheme was developed under a bee colony algorithm, namely PEGASIS Artificial Bee Colony (PEG_ABC). It aimed to minimize transmission delay based on three factors: Euclidean distance between the base station and sensors, Euclidean distance between sensors, and the remaining sensor energy. These key factors are implemented for chain leader choice at the first level, where the fitness function of the bee colony algorithm is adjusted regularly. The second level is associated with transmitting the collected data between chain leaders. The method showed superior performance with respect to the number of packets sent to BS, energy consumption, transmission delay, and network lifetime.

Rajkumar et al. [50] proposed an evolutionary algorithm to tackle the challenges of dynamic path discovery in WSNs. That approach used chromosome detection techniques to develop routing paths by employing crossover and mutation processes, which mimic genetic operations to refine data transmission routes. Rather than prioritizing the shortest path, the method emphasized progressive route discovery and robust convergence. The study highlighted that variability in the first population can complicate the search space.

2. Discussion and Future Trend

In the context of WSNs, evaluating performance and optimization requires a structured approach using well-defined metrics. Table 1 *demonstrates the key metrics discussed in the literature.* These metrics are typically categorized into three principal areas: clustering metrics, routing metrics, and performance metrics. Below, these categories are introduced and defined:

1. Clustering Metrics: Metrics under this category evaluate the efficiency of cluster formation and maintenance in a WSN. Key metrics include:

- *Node Degree:* Measures the number of direct connections a node has within a cluster.
- *Centrality:* Shows the essential role of a node in the network structure.
- *Residual Energy:* Tracks the remaining energy of nodes to apply efficient cluster head choice.
- *Compactness:* Refers to the proximity of nodes within a cluster, ensuring minimal intra-cluster communication overhead.

2. Routing Metrics: These metrics assess the robustness and efficiency of data transmission paths in the network. Examples include:

- *Path Quality:* Evaluates the reliability and stability of routing paths.
- *Connection Stability:* Measures the likelihood of keeping a connection over time.
- *Optimal Path Selection:* Finds the shortest and most energy-efficient paths for data transmission.

3. Performance Metrics: This category focuses on the overall efficiency and effectiveness of the WSN. Metrics include:

- *Packet Delivery Ratio (PDR):* The percentage of successfully delivered data packets.

$$PDR = \frac{Number\ of\ packts\ received\ at\ the\ destination}{Number\ of\ the\ packets\ sent\ from\ source\ node}$$

- *Delay/Latency:* The time occupied for data to reach its destination.

$$Average\ packet\ delay = Received\ time - Send\ time$$

- *Network Lifetime:* The operational duration of the network before critical nodes fail due to energy depletion.
- *Throughput:* the maximum rate at which data can be transmitted over a network. It is the duration taken for a data packet to transmit from its origin to its destination.

$$PDR = \frac{Amount\ of\ packet\ sent}{time\ taken\ to\ transmit\ a\ packet}$$

Table 1.
Key Metrics used in the literature review for Energy-Efficient Routing in Wireless Sensor Networks.

No.	Metric	Category	Key References
1	Node Degree	Clustering Metrics	Raj and Duraipandian [17] and Gül [45]
2	Residual Energy	Clustering Metrics	Lee [29] and Suman et al. [48]
3	Relay Distance	Clustering Metrics	Saemi and Goodarzian [8] and Suman et al. [48]
4	Compactness	Clustering Metrics	Ali et al. [14] and Raji and Taofeek-Ibrahim [9]
5	Cluster Formation	Clustering Metrics	Somula et al. [20] and Jing [40]
6	Path Quality	Routing Metrics	Al-Heeti et al. [25] and Kaur [32]
7	Optimal Path Selection	Routing Metrics	Ketshabetswe et al. [10] and Pal et al. [13]
8	Delay Minimization	Routing Metrics	Lee [29] and Ramezanzadeh and Shokrzadeh [49]
9	Energy Consumption	Performance Metrics	Janarthanan and Srinivasan [15] and Gangal et al. [27]
10	Packet Delivery Ratio	Performance Metrics	Suresh et al. [24] and Kaur [32]

2.1. Research Gap

Despite significant advances, several gaps remain in the optimization of WSNs:

- *Energy Imbalance*: Many studies do not address energy imbalances caused by uneven workload distribution among nodes.

- *Dynamic Environments:* Limited research has focused on protocols adaptable to highly dynamic and unpredictable environmental conditions.
- *Integration of Advanced Techniques:* While artificial intelligence and machine learning show promise, their integration into WSNs remains underexplored due to computational constraints.
- *Comprehensive Evaluation Metrics:* Existing studies often focus on a subset of metrics, neglecting holistic evaluations that combine clustering, routing, and overall performance.

2.2. Future Trends

To address these gaps, the following future trends are recommended:

- *Energy-Aware Algorithms:* Develop algorithms that dynamically balance energy consumption across all nodes, extending network lifetime.
- *AI-Driven Protocols:* Leverage machine learning techniques for adaptive routing and clustering to enhance efficiency in dynamic environments.
- *Hybrid Metrics Frameworks:* Set up frameworks combining clustering, routing, and performance metrics for comprehensive protocol evaluations.
- *Low-Power Computing Solutions:* Integrate low-power AI processors to enable computationally intensive tasks like data fusion and anomaly detection.
- *Real-Time Monitoring Systems:* Focus on real-time systems capable of detecting and responding to network failures promptly.

By focusing on these areas, future research can further enhance the reliability, scalability, and energy efficiency of WSNs while addressing existing challenges.

3. Conclusion

This review has examined several energy-efficient clustering and routing techniques in WSNs. The study has highlighted the primary challenges that WSNs face, particularly in relation to energy consumption, network durability, and data transmission efficiency. It has been investigated how well several clustering and routing algorithms, including heuristic and AI-based approaches, maximize energy use and enhance network performance.

Several research gaps remain despite considerable progress in energy-efficient protocols, including the need for adaptive solutions that can perform well in dynamic environments, the integration of state-of-the-art AI techniques within WSNs, and the development of comprehensive evaluation frameworks that consider multiple performance metrics simultaneously.

Future research should focus on developing energy-conscious algorithms, applying AI for astute routing and clustering, and integrating low-power computing technologies to increase network efficiency. Furthermore, real-time monitoring systems and hybrid metrics frameworks may significantly improve the reliability, scalability, and durability of WSNs across a range of application situations.

By addressing these problems, researchers can advance the field of WSNs and deliver more dependable and sustainable network operations in the future.

References

[1] M. Maaz, G. Ahmed, A. S. Al-Shamayleh, A. Akhunzada, S. Siddiqui, and A. H. Al-Ghushami, "Empowering IoT resilience: Hybrid deep learning techniques for enhanced security," *IEEE Access,* 2024.

[2] M. A. AlHija, H. J. Alqudah, and H. Dar-Othman, "Uncovering botnets in IoT sensor networks: a hybrid self-organizing maps approach," *Indonesian Journal of Electrical Engineering and Computer Science,* vol. 34, no. 3, pp. 1840-1857, 2024.

[3] A. Dhingra, A. Sangwan, and V. Sindhu, "A detailed review and comparative analysis of various energyefficient clustering protocols in wireless sensor networks," 2024.

[4] M. Razzaq and S. Shin, "Fuzzy-logic dijkstra-based energy-efficient algorithm for data transmission in WSNs," *Sensors,* vol. 19, no. 5, p. 1040, 2019.

[5] N. A. Pantazis, S. A. Nikolidakis, and D. D. Vergados, "Energy-efficient routing protocols in wireless sensor networks: A survey," *IEEE Communications Surveys & Tutorials,* vol. 15, no. 2, pp. 551-591, 2012.

[6] N. Meenakshi *et al.*, "Efficient communication in wireless sensor networks using optimized energy efficient engroove leach clustering protocol," *Tsinghua Science and Technology,* vol. 29, no. 4, pp. 985-1001, 2024.

[7] H. Hu, X. Fan, and C. Wang, "Energy efficient clustering and routing protocol based on quantum particle swarm optimization and fuzzy logic for wireless sensor networks," *Scientific Reports,* vol. 14, no. 1, p. 18595, 2024.

[8] B. Saemi and F. Goodarzian, "Energy-efficient routing protocol for underwater wireless sensor networks using a hybrid metaheuristic algorithm," *Engineering applications of artificial intelligence,* vol. 133, p. 108132, 2024.

[9] A. K. Raji and F. A. Taofeek-Ibrahim, "Enhancing the lifetime and efficiency of wireless sensor networks using ai-integrated CRT-LEACH protocols," *TETFund/ESS/POLY/BONNY/ARJ/3 TETFund/DESS/POLY/BONNY/ARJ/2017-2024,* p. 40, 2024.

[10] L. K. Ketshabetswe, A. M. Zungeru, C. K. Lebekwe, and B. Mtengi, "A compression-based routing strategy for energy saving in wireless sensor networks," *Results in Engineering,* vol. 23, p. 102616, 2024.

[11] K. Sharada, T. Mahesh, S. Chandrasekaran, R. Shashikumar, V. V. Kumar, and J. R. Annand, "Improved energy efficiency using adaptive ant colony distributed intelligent based clustering in wireless sensor networks," *Scientific Reports,* vol. 14, no. 1, p. 4391, 2024.

[12] S. H. Gopalan, D. G. Takale, B. Jayaprakash, and V. P. Raj, "An energy efficient routing protocol with fuzzy neural networks in wireless sensor network," *Ain Shams Engineering Journal,* vol. 15, no. 10, p. 102979, 2024.

[13] R. Pal, M. Saraswat, S. Kumar, A. Nayyar, and P. K. Rajput, "Energy efficient multi-criterion binary grey wolf optimizer based clustering for heterogeneous wireless sensor networks," *Soft Computing,* vol. 28, no. 4, pp. 3251-3265, 2024.

[14] A. Ali *et al.*, "Enhanced fuzzy logic zone stable election protocol for cluster head election (E-FLZSEPFCH) and multipath routing in wireless sensor networks," *Ain Shams Engineering Journal,* vol. 15, no. 2, p. 102356, 2024.

[15] A. Janarthanan and V. Srinivasan, "Multi-objective cluster head-based energy aware routing using optimized auto-metric graph neural network for secured data aggregation in Wireless Sensor Network," *International Journal of Communication Systems,* vol. 37, no. 3, p. e5664, 2024.

[16] I. Surenther, K. Sridhar, and M. K. Roberts, "Enhancing data transmission efficiency in wireless sensor networks through machine learning-enabled energy optimization: A grouping model approach," *Ain Shams Engineering Journal,* vol. 15, no. 4, p. 102644, 2024.

[17] V. P. Raj and M. Duraipandian, "An energy-efficient cross-layer-based opportunistic routing protocol and partially informed sparse autoencoder for data transfer in wireless sensor network," *Journal of Engineering Research,* vol. 12, no. 1, pp. 122-132, 2024.

[18] M. Tolani, S. A. A. Biabani, and P. Kumar, "Energy-efficient deviation aware adaptive bit-mapping medium access control protocol for wireless sensor network," *IEEE Access,* 2024.

[19] F. M. Salman, A. A. Mohammed, and F. A. Joda, "ESMCH: An energy-saving, multi-hop, clustering, and hierarchy protocol for homogeneous WSNs," *Iraqi Journal of Science,* pp. 3451-3467, 2024.

[20] R. Somula, Y. Cho, and B. K. Mohanta, "SWARAM: osprey optimization algorithm-based energy-efficient cluster head selection for wireless sensor network-based internet of things," *Sensors,* vol. 24, no. 2, 2024.

[21] K. K. Almuzaini *et al.*, "Optimization of the operational state's routing for mobile wireless sensor networks," *Wireless Networks,* vol. 30, no. 6, pp. 5247-5261, 2024.

[22] S. Babatunde, A. Alsubhi, J. Hester, and J. Sorber, "Greentooth: Robust and energy efficient wireless networking for batteryless devices," *ACM Transactions on Sensor Networks,* vol. 20, no. 3, pp. 1-31, 2024.

[23] R. Rizky, Z. Hakim, S. Setiyowati, and A. M. Yunita, "Development of the multi-channel clustering hierarchy method for increasing performance in wireless sensor network," *MATRIK: Jurnal Manajemen, Teknik Informatika Dan Rekayasa Komputer,* vol. 23, no. 3, pp. 603-614, 2024.

[24] S. S. Suresh, V. Prabhu, V. Parthasarathy, G. Senthilkumar, and V. Gundu, "Intelligent data routing strategy based on federated deep reinforcement learning for IOT-enabled wireless sensor networks," *Measurement: Sensors,* vol. 31, p. 101012, 2024.

[25] M. M. Al-Heeti, J. A. Hammad, and A. S. Mustafa, "Design and implementation of energy-efficient hybrid data aggregation in heterogeneous wireless sensor network," *Bulletin of Electrical Engineering and Informatics,* vol. 13, no. 2, pp. 1392-1399, 2024.

[26] L. Sahoo, S. S. Sen, K. Tiwary, S. Moslem, and T. Senapati, "Improvement of wireless sensor network lifetime via intelligent clustering under uncertainty," *IEEE Access,* vol. 12, pp. 25018-25033, 2024.

[27] V. Gangal, I. Cinemre, and G. Hacioglu, "A distributed leach-ahp routing for wireless sensor networks," *IEEE Access,* vol. 12, pp. 19307-19319, 2024.

[28] M. Preetha, K. Murugesan, and R. A. Kumar, "Contextual attention greylag goose neural networks based efficient energy consumption and fault tolerant method for clustering and reliable routing in wireless sensor network," *Library of Progress-Library Science, Information Technology & Computer,* vol. 44, no. 3, 2024.

[29] J.-H. Lee, "Clustering uniformity methods for energy efficiency in wireless sensor networks," 2024.

[30] D. Liu, C. Liang, H. Mo, X. Chen, D. Kong, and P. Chen, "LEACH-D: A low-energy, low-delay data transmission method for industrial internet of things wireless sensors," *Internet of Things and Cyber-Physical Systems,* vol. 4, pp. 129-137, 2024.

[31] J. B. Fernandes, B. Gopi, M. A. Shariff, M. R. Pasha, S. Srinivasan, and S. P. Maniraj, "Reliable and efficient routing for water quality monitoring in underwater WSN," presented at the In 2024 2nd International Conference on Computer, Communication and Control (IC4), IEEE, 2024, pp. 1–5, 2024.

[32] G. Kaur, "Enhancing energy use efficiency of wireless sensor networks using newly proposed fault tolerance multipath routing protocol (MRP-FT)," *Operations Research and Decisions,* vol. 34, no. 3, pp. 143-164, 2024. https://doi.org/10.37190/ord240308

[33] A. Gupta and R. K. Yadav, "Mathematical modeling and statistical analysis of efficient cluster head selection based leach protocol for wireless sensor networks," n.d.

[34] Z. Ma, Z. Hao, and Z. Zhao, "An investigation on energy-saving scheduling algorithm of wireless monitoring sensors in oil and gas pipeline networks," *Energy Informatics,* vol. 7, no. 1, p. 104, 2024.

[35] P. P. Bairagi, M. Dutta, and K. S. Babulal, "An energy-efficient protocol based on recursive geographic forwarding mechanisms for improving routing performance in WSN," *IETE Journal of Research,* vol. 70, no. 3, pp. 2212-2224, 2024.

[36] K. Haghzad, S Javadian, M, "Improvement of low energy adaptive clustering hierarchical protocol based on genetic algorithm to increase network lifetime of wireless sensor network," *Int J Eng,* vol. 37, no. 9, pp. 1800-1811, 2024.

[37] S. Vhatkar, Z. Aalam, and M. Atique, "Advancing Wireless Sensor Networks through Performance Evaluation of M-PDCH Routing Protocol for Enhanced Quality of Service," *Indian Journal of Science and Technology,* vol. 17, no. 9, pp. 794-803, 2024.

[38] H. Majid Lateef and K. M. Al-Qurabat, "Optimizing cluster head selection for enhanced energy efficiency in WSNs through AHP and TOPSIS techniques," *International Journal of Computing and Digital Systems,* vol. 16, no. 1, pp. 595-607, 2024.

[39] A. N. Pathak and A. R. Yadav, "Scheduling based on residual energy of sensors to extend the lifetime of network in wireless sensor network," *Journal of Engineering and Applied Science,* vol. 71, no. 1, p. 100, 2024.

[40] D. Jing, "Harris harks optimization based clustering with fuzzy routing for lifetime enhancing in wireless sensor networks," *IEEE Access,* vol. 12, pp. 12149-12163, 2024.

[41] S. Shen and F. Xu, "A low energy security-aware routing protocol based on grey clustering analysis in WSNs," 2024.

[42] A. M. Shah and F. Afzal, "Energy efficient routing using game theory for wireless sensor networks," 2024.

[43] A. Dubey, "Secure and efficient routing in wireless sensor networks: Ld2fa-pso intrusion detection and cluster headselection," 2024.

[44] R. P. S. Hada and A. Srivastava, "Dynamic Cluster Head Selection in WSN," *ACM Transactions on Embedded Computing Systems,* vol. 23, no. 4, pp. 1-27, 2024.

[45] Ö. M. Gül, "A novel energy-aware path planning by autonomous underwater vehicle in underwater wireless sensor networks," *Turkish Journal of Maritime and Marine Sciences,* vol. 10, no. Özel Sayı: 1, pp. 81-94, 2024.

[46] R. Sridevi and V. Prakash, "Load aware active low energy adaptive clustering hierarchy for IoT-WSN," *The Scientific Temper,* vol. 15, no. 02, pp. 2123-2131, 2024.

[47] H. K. Sivaraman and R. Leburu, "Energy-efficient clustering and routing using fuzzy k-medoids and adaptive ranking-based wireless sensor network," *Int J Reconfigurable & Embedded Syst ISSN,* vol. 2089, no. 4864, p. 4864, 2024.
[48] M. A. N. Suman, V. Geethasri, and A. S. A. I. Pavan, "A routing protocol for efficiently managing energy in underwater wireless sensor networks with depth control," *Journal of Science & Technology,* vol. 9, no. 4, pp. 59–73, 2024.
[49] F. Ramezanzadeh and H. Shokrzadeh, "Efficient routing method for IoT networks using bee colony and hierarchical chain clustering algorithm," *E-Prime-Advances in Electrical Engineering, Electronics and Energy,* vol. 7, p. 100424, 2024.
[50] D. U. S. Rajkumar, K. P. Karani, R. Sathiyaraj, and P. Vidyullatha, "Optimal shortest path selection using an evolutionary algorithm in wireless sensor networks," *International Journal of Electrical & Computer Engineering (2088-8708),* vol. 14, no. 6, 2024.