
ENERGY-EFFICIENT COMMUNICATION AND ROUTING STRATEGIES IN HETEROGENEOUS WIRELESS SENSOR NETWORKS: A COMPREHENSIVE REVIEW

**Matthew Iyobhebhe^{1,*}, Abdoulie Momodou. S. Tekanyi², Athanisius Terlumun Utev²,
Fatima Ashafa¹, Asebakeoghene. J. Khama¹, Botson Ishaya Chollom¹, Umar Salisu
Lawal¹**

¹Federal Polytechnic Nasarawa, Nigeria

²Ahmadu Bello University, Zaria, Nigeria, Faculty of Engineering, Department of Electronics and
Telecommunications Engineering

Email: mattoiyobhe@gmail.com*, amtekany@abu.edu.ng, utev@gmail.com, fatima@gmail.com,
ase@gmail.com, botson@gmail.com, umar@gmail.com

***Corresponding author:** Matthew Iyobhebhe

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ABSTRACT

Heterogeneous Wireless Sensor Networks (HWSNs) have attracted significant attention because they can improve network performance and maximize operational lifetime by combining sensor nodes with diverse capabilities. However, node heterogeneity introduces new challenges for designing energy-efficient communication and routing mechanisms, especially under stringent energy constraints. This review introduces a comprehensive scrutiny of existing communication and routing strategies in HWSNs, with a primary focus on energy efficiency and sustainability. The study systematically scrutinizes fundamental HWSN concepts, energy consumption models, communication paradigms, and routing protocols, including flat and hierarchical approaches. Furthermore, recent improvements in energy harvesting, harvesting-aware routing, and hybrid energy storage systems are considered key enablers of sustainable network operation. By combining conventional and emerging techniques, this review identifies critical research challenges and future directions, offering valuable insights for researchers and system designers toward the development of scalable, adaptive, and energy-efficient HWSN solutions.

Keywords: Communication strategies; Cross-layer communication approaches; Energy harvesting in HWSNs; Energy-efficient in HWSNs; Energy consumption models in HWSNs; heterogeneity in HWSNs; Routing strategies in HWSNs

1. INTRODUCTION

Wireless Sensor Networks (WSNs) have evolved as a vital technology system, enabling a wide range of implementations, including environmental monitoring, industrial automation, smart agriculture, medical healthcare, and intelligent transportation systems. These networks classically consist of spatially dispersed sensor nodes that collectively sense, process, and send packets to a sink or base station (Soni Chaurasia *et al.*, 2025). A dire limitation of traditional homogeneous WSNs is their unembellished energy-limited nature, as sensor nodes are usually battery-powered and positioned in harsh or inaccessible environments where battery replacement is impractical. To address the scalability and operational challenges inherent in homogeneous organizations, HWSNs, where sensor nodes vary in terms of energy capacity, communication range, processing capability, or functional tasks, have been extensively adopted in current research and real-world implementations. Despite their benefits, HWSNs present new limitations in energy-efficient communication and routing. The introduction of nodes with unequal abilities results in unbalanced energy utilization, predominantly for rich-energy nodes that are often selected as Cluster Heads (CH), relays, or gateways. This imbalance frequently leads to early node failures, hotspot formation near the sink, minimized network lifetime, and poor network service. Consequently, designing communication and routing schemes that logically exploit node heterogeneity while mitigating overall energy depletion remains a serious and unresolved research problem (Yang Zhang *et al.*, 2025). The motivation for this

review stems from the swift increase of energy-aware communication and routing methods tailored for HWSNs, stretching from traditional clustering-based protocols to current optimization-based and intelligent schemes. Although various articles have addressed energy efficiency in HWSNs, existing studies repeatedly focus on specific protocol categories or lack an integrated comparative perspective that captures communication mechanisms, routing strategies, performance metrics, and emerging intelligent techniques within a unified framework (Namit Gupta *et al.*, 2025, Aveneesh Singh *et al.*, 2025). This gap led us to a holistic review that systematically categorizes and critically analyzes these methods, underscoring their strengths, limitations, and suitability for diverse implementation scenarios. To address this gap, this review embraces a structured and comparative methodology. The review first defines fundamental concepts, energy models, and evaluation metrics pertinent to HWSNs. It then categorizes and analyzes energy-efficient communication strategies, followed by an in-depth review of routing protocols, including flat, hierarchical, and hybrid approaches. Current advances in energy harvesting-aware techniques are also examined to reflect current research trends. The chosen classification framework allows clear comparison across techniques in terms of energy usage, scalability, adaptability, and application complexity, thereby justifying the selection of these approaches as representative and impactful solutions in contemporary HWSN research. The key contribution of this review lies in its holistic synthesis of energy-efficient communication and routing strategies in HWSNs (Sumendra Thakur *et al.*, 2025, Avaneesh Singh *et al.*, 2025, M. Karthikeyan *et al.*, 2025). Unlike prior works, this paper integrates conventional and intelligent approaches, identifies open research challenges, and outlines promising future directions, particularly in the context of IoT integration and autonomous network management. The findings presented in this study are relevant to researchers, practitioners, and system designers seeking to develop sustainable, scalable, and high-performance HWSNs (Aarti Sharma *et al.*, 2025, Raghuveer Singh *et al.*, 2025, Ayman A. Alharibi *et al.*, 2025, Yihan Guan *et al.*, 2025). By providing a comprehensive reference and comparative insight, this review aims to support informed decision-making and stimulate further innovation in energy-efficient HWSN design.

2. REVIEW METHODOLOGY

This study used an organized literature-review methodology to identify, evaluate, screen, and synthesize research related to routing techniques and energy-efficient communication in HWSNs. Relevant literatures was extracted from major scientific databases, including Web of Science, ScienceDirect, IEEE Xplore, and Google Scholar. The search was conducted using combinations of keywords such as: Energy-efficient routing, energy harvesting, HWSNs, sustainable HWSNs, machine learning routing in WSN, energy-aware communication, and adaptive communication.

The literatures search was limited to publications between 2020 to 2026 to capture recent developments in energy-efficient HWSN design. Studies were included if they:

- Addressed energy-efficient communication or routing in WSNs/HWSNs.
- Reported performance metrics such as energy consumption, network lifetime, throughput, packet delivery ratio, or delay.
- Presented simulation, analytical, or experimental validation.

Studies were excluded if they:

- Focused solely on hardware implementation.
- Did not report energy-related performance metrics.
- Were duplicate publications.

The selection process followed four stages:

- Identification
- Screening
- Eligibility Assessment
- Final inclusion

The retrieved records were initially screened using their titles and abstracts. Duplicate records were removed before detailed assessment. The remaining studies were examined against the inclusion and exclusion criteria, followed by full-text assessment of potentially relevant publications. Table 1 depict PRISMA-Style summary.

Table 1: PRISMA-Style Summary

Stage	Number of Studies
Records identified	52
Duplicates removed	14
Records Screened	38
Full-text Reviewed	9
Final studies included	29

2.1. Review

Muhammad Haris & Haewoon Nam (2025) proposed an optimized particle swarm optimization (PSO)-based CH selection structure to enhance energy efficiency in IoT-based WSNs. Their method dynamically selects CHs based on residual energy and communication cost, resulting in balanced energy expenditure and prolonged network lifetime. Simulation results show that the developed scheme outperforms LEACH by approximately 28%, LEACH-FL and LEACH-FC by around 20%, and KM-PSO by nearly 10% in terms of nodes survivability and network lifetime. However, the study primarily targets homogeneous IoT-WSNs, with limited emphasis on heterogeneity-aware design and cross-layer energy optimization, which are critical in HWSN environments and also face challenges such as balancing fairness among nodes, managing heterogeneous harvesting rates, and guaranteeing reliable operation under changing environmental conditions

I.Gethzi Ahila Poornima et al., (2025) proposed an energy-efficient hybrid optimization-based routing framework for IoT-based WBANs. Their model incorporates intelligent optimization techniques to realize optimal routing decisions, leading to minimized energy utilization and enhanced network lifetime. However, the work is application-specific to WBANs and does not explicitly address heterogeneous node capabilities or large-scale multi-hop scenarios typical of HWSNs, and also faced with challenges comprise balancing fairness among nodes, managing heterogeneous harvesting rates, and guaranteeing reliable operation under changing environmental conditions.

P.K. Poonguszhali et al., (2025) presented a multi-objective, CH-based energy-efficient routing framework that combines a deep convolutional neural network (THDCNN) with hybrid Capuchin Search and Woodpecker Mating algorithms. The proposed method jointly optimizes CH selection and routing to reduce energy utilization while optimizing network stability and throughput. Simulation results show that the developed scheme outperformance with and attains 25.3, 10.76, 45.67, 49.15, 50.12 and 35% higher alive nodes and 22.32, 16.76, 27.67, 11.71, 30.32, and 27.02% higher detection rate when compared with existing methods. However, the study is primarily evaluated on homogeneous WSN settings, with limited consideration of node heterogeneity and practical deployment constraints in large-scale HWSNs, and also faced with challenges comprise balancing fairness among nodes, managing heterogeneous harvesting rates, and guaranteeing reliable operation under changing environmental conditions..

Sunawar Khan et al., (2025), examined the integration of IoT and WSN architectures with the objective of optimizing quality of service via improved energy efficiency, scalability, and secure communication techniques. The study proposes a layered framework that enhances data communication and resource utilization in smart system environments. Simulation results show superior improvements in throughput, latency, and energy consumption compared to conventional IoT-WSN models. However, the work provides a system-level perspective and lacks detailed analysis of heterogeneity-aware routing and energy harvesting strategies essential for sustainable HWSNs, and also faces challenges comprising balancing fairness among nodes, managing heterogeneous harvesting rates, and guaranteeing reliable operation under changing environmental conditions.

Muhammad Akram et al., (2025), the researchers proposed EEMLCR, an energy-efficient machine learning-based clustering and routing framework for wireless sensor networks. The technique leverages supervised learning to enhance CH selection and adaptive routing decisions, leading to optimized energy consumption and prolonged network lifetime. The developed scheme when compared with existing schemes, after 600 rounds in networks comprising 400 nodes, the developed scheme showed significant improvements. However, the model is primarily validated on homogeneous WSN scenarios and does not explicitly incorporate heterogeneity-aware energy

management or harvesting-based sustainability mechanisms relevant to HWSNs, and also faced with challenges comprise balancing fairness among nodes, managing heterogeneous harvesting rates, and guaranteeing reliable operation under changing environmental conditions.

Potu Arayana et al. (2026) estimated their secured energy-efficient opportunistic routing scheme using QualNet 5.02 and NS-2.34 with 50, 100, and 200 nodes under normal and attack scenarios. The simulation results showed higher throughput and lower average end-to-end delay than EEFCR, with performance remaining more stable as node speed and network dynamics increased. The proposed scheme also demonstrated improved energy efficiency through reduced unnecessary transmissions and better residual-energy preservation, thereby extending network lifetime. Quantitatively, the scheme was reported to be 2-3% faster than DLAMD and 10-13% faster than EEFCR, while its malware detection rate improved by approximately 23%. These results indicate that the proposed approach provides a better balance of throughput, delay, energy consumption, network lifetime, and security for WSNs, and also faces challenges comprise balancing fairness among nodes, managing heterogeneous harvesting rates, and guaranteeing reliable operation under changing environmental conditions.

Yang Zhang et al., (2025) proposed an energy-efficient adaptive routing framework for heterogeneous wireless sensor networks by integrating an Improved Particle Swarm Optimization (IPSO)-based cluster-head selection mechanism with dynamic clustering and hybrid single-/multi-hop routing. The framework was evaluated using 200 heterogeneous nodes deployed over a $200 \times 200 \text{ m}^2$ area, comprising low-power sensors (0.5 J), battery-powered relays (1.0 J), and solar-powered hubs (2.0 J). Simulation results showed a 32.7% reduction in per-round energy consumption compared with LEACH, a 28% improvement in network lifetime based on the first-node-death metric, and a 63% reduction in energy variance among nodes. At a 20% solar-powered-hub proportion, the half-node-death lifetime increased by $36.8 \pm 2.1\%$, from $1,518 \pm 42$ to $2,075 \pm 55$ rounds. The framework also demonstrated practical computational feasibility, with IPSO requiring $0.82 \pm 0.07 \text{ ms}$ per iteration on a Raspberry Pi 4B. However, the approach remains computationally dependent on gateway/edge nodes and primarily targets static HWSNs, indicating opportunities for lightweight distributed coordination and broader real-world validation.

Lina Elmoiz Alatabani et al. (2026) investigated cross-layer optimization using energy-efficient routing protocols for WSNs, focusing on interactions among network, MAC, and physical-layer operations. The chapter evaluates clustered routing protocols to examine their effects on throughput, average end-to-end delay, energy consumption, and network lifetime. Its analysis emphasizes the potential of cross-layer coordination to improve QoS while reducing energy expenditure and extending network lifetime. Therefore, the study provides a useful conceptual basis for cross-layer energy optimization, but its quantitative performance claims should be verified from the full chapter before inclusion in a comparative results table, and it also faces challenges comprise balancing fairness among nodes, managing heterogeneous harvesting rates, and guaranteeing reliable operation under changing environmental conditions.

Tumpa Pal et al. (2026) conducted a PRISMA-based systematic review of 43 high-quality studies on energy-efficient WSN routing for precision and smart agriculture, selected from an initial 250 studies published between 2016 and 2025. The reviewed protocols were evaluated mainly using network lifetime, energy consumption, packet delivery ratio (PDR), throughput, latency, routing overhead, and coverage. Quantitative evidence reported in the review indicates that a Dynamic Energy-based Clustering approach achieved 30-40% lower energy consumption, 50% longer network lifetime, and 90-98% PDR compared with traditional routing protocols. Across the reviewed studies, 15 clustering-based, 8 optimization-based, 5 fuzzy-based, 5 ML-based, 5 security-aware, and 5 hybrid approaches were identified. The review concluded that clustering and optimization methods provide strong energy and lifetime benefits, whereas ML and hybrid approaches offer improved adaptability and scalability for dynamic agricultural environments, and also faced with challenges comprise balancing fairness among nodes, managing heterogeneous harvesting rates, and guaranteeing reliable operation under changing environmental conditions.

The nine studies discussed above provide representative evidence of the principal approaches identified across the 29 included studies. The remaining studies were synthesized collectively rather than discussed individually to avoid repetitive descriptions and to maintain focus on the dominant methodological trends.

In summary, the reviewed articles show substantial progress in energy-efficient clustering, routing, and intelligent optimization for WSNs and IoT-based networks. However, most prior works are application-specific or assume homogeneous network settings, with limited consideration of node heterogeneity, harvesting-aware operation, and cross-layer energy optimization. This review addresses these gaps by providing a unified and comprehensive analysis of energy-efficient communication and routing strategies specifically tailored for sustainable Heterogeneous Wireless Sensor Networks.

3. FUNDAMENTALS OF HETEROGENEOUS WIRELESS SENSOR NETWORKS

HWSNs show a significant development of conventional wireless sensor network design, motivated by the need to enhance energy efficiency, scalability, and network longevity in resource-limited environments (Maryam Shafiq *et al.*, 2021). Unlike homogeneous WSNs, where all sensor nodes are the same in capability and task, HWSNs deliberately integrate nodes with varied energy capacities, processing power, communication ranges, and sensing functions. These variations allow the network to better adapt to different traffic loads and implementation requirements, making HWSNs predominantly suitable for large-scale and long-term deployments (Maria Trigk *et al.*, 2025).

3.1. Definition and Characteristics of HWSNs

HWSNs are an integral part of conventional WSNs in which sensor nodes have varying capabilities in terms of energy resources, processing power, communication range, memory, or functional roles. Unlike homogeneous WSNs, where all nodes are the same in terms of network resources, HWSNs deliberately use node variations to enhance network performance, scalability, and longevity (Bilal R. Al-Kaseem *et al.*, 2021). Typical characteristics of HWSNs comprise unequal initial energy levels, role differentiation for example, “normal nodes, advanced nodes, super nodes”, adaptive communication ranges, and hierarchical data forwarding. These characteristics enable more efficient task allotment and energy usage, but also introduce complexity in communication and routing design (D. Pravin Kumar *et al.*, 2025).

3.2. Types of Heterogeneity in HWSNs

Heterogeneity in HWSNs discusses the careful integration of sensor nodes with different capabilities and resources within the same network. In HWSNs, such variation leads to enhanced operation, energy efficiency, and scalability. These variations may exist in energy resources, computation, communication, or functional tasks assigned to nodes. Comprehending the types of heterogeneity is crucial for designing effective communication and routing strategies that fully exploit node diversity while minimizing energy imbalance. Table 2 briefly describes the subsection (Abdulla Juwaieda *et al.*, 2025).

Table 2: Types of heterogeneity in HWSNs

Type of heterogeneity	Description	Impact on Network Performance
Energy heterogeneity	Nodes are equipped with varying energy levels	Improves network lifetime but may cause energy imbalance
Computational heterogeneity	Nodes vary in processing and memory capacity	Enables local packets and intelligent routing
Communication heterogeneity	Nodes have different transmission power and range	Enhances connectivity and coverage
Functional heterogeneity	Nodes perform specialized roles (CHs, gateways)	Improves efficiency and data aggregation
Hardware heterogeneity	Varying sensor types and hardware platform	Supports diverse sensing applications

3.3. Network Architectures and Deployment Models

HWSNs are regularly structured using flat, hierarchical, or hybrid architectures. In flat architectures, all nodes execute similar networking functions despite basic heterogeneity, which simplifies design but may underutilize high-rich nodes. Hierarchical architectures, such as clustering-based models, assign energy-rich or high-capability nodes as cluster heads or relay nodes, enabling efficient data aggregation and reduced transmission overhead. Hybrid architectures integrate flat and hierarchical features to balance flexibility and energy efficiency. Deployment models in HWSNs may be deterministic (organized placement of rich-energy nodes at strategic locations) or random, often followed by adaptive role assignment. Strategic deployment of powerful nodes near the sink or in high-traffic regions is commonly used to mitigate hotspot and bottleneck problems (Nisha B. *et al.*, 2025).

3.4. Energy Consumption Models in HWSNs

Energy utilization modeling is vital to the design and estimation of energy-efficient protocols in HWSNs. Most articles embrace a first-order radio energy model, where energy dissipation relies on both electronic circuitry and communication distance. The energy utilized to transmit a k -bit data packet over distance d is given in equation (1) (Xiaoying Liu *et al.*, 2025):

$$E_{tx}(k, d) = \begin{cases} kE_{ele} + kE_{fs}^{d^2}, & d < d_0 \\ kE_{ele} + kE_{mp}^{d^4}, & d \geq d_0 \end{cases} \quad (1)$$

The energy utilized to receive the same data is given in equation (2):

$$E_{rx}(k) = kE_{ele} \quad (2)$$

Where E_{ele} signifies the energy utilized by transmitter/receiver electronics, E_{fs} and E_{mp} defines the free-space and multipath fading amplification coefficient, respectively, and d_0 denotes the threshold distance. In HWSNs, nodes with higher residual energy or improved hardware are often designated with more energy-intensive tasks, thereby ensuring accurate energy modeling critical for fair load distribution and maximized network lifetime (Ali Forghani *et al.*, 2022).

4. COMMUNICATION STRATEGIES IN HWSNS

Efficient transmission is a foundation of energy conservation in HWSNs, as data communication typically dominates overall energy usage. The presence of nodes with varying capabilities allows flexible transmission designs that can use rich-energy or rich-capacity nodes for energy-intensive tasks. This section reviews key communication strategies used in HWSNs, accentuating their functional principles, advantages, and energy-efficiency implications.

4.1. Single-Hop vs. Multi-Hop Communication

Single-hop and multi-hop transmission introduce two vital data delivery paradigms in HWSNs. In single-hop transmission, sensor nodes transmit data directly to the sink/base station (BS), which simplifies routing but suffers high energy utilization costs for distant nodes. Multi-hop transmission, on the other hand, transmits data via intermediate nodes, minimizing communication distance per hop and enhancing scalability. In HWSNs, node heterogeneity enables high energy-resource nodes to function as relays, thereby balancing energy usage and minimizing hotspot problems. Table 3 briefly describes single-hop and multi-hop communications.

Table 3: Single-hop and multi-hop communications

Communication Mode	Description	Energy Implication	Sustainability in HWSNs
Single-hop	Direct node-to-sink transmission	High energy cost for distance nodes	Small-scale or dense networks
Multi-hop	Data forward via intermediate nodes	Lower per-hop energy usage	Large-scale heterogeneous deployments

4.2.Data Aggregation and Fusion Techniques

Data aggregation and fusion techniques aim to minimize redundant communications by integrating data from numerous sensor nodes before forwarding it to the BS. By using spatial and temporal data correlation, these methods meaningfully lower communication overhead and energy usage. In HWSNs, nodes with higher processing ability are typically allocated aggregation tasks, enhancing efficiency without overburdening resource-limited nodes. Table 4 briefly defines data aggregation and fusion techniques (Tumpa Pal *et al*, 2026).

Table 4: Data aggregation and Fusion techniques

Technique	Operation	Energy Benefit	Typical Aggregator Node
Data Aggregation	Summarization (average, min.	Reduces packets count max	Cluster heads
Data Fusion	Intelligent combination of multi-sensor data	Improves data quality and efficiency	Advanced nodes

4.3. Adaptive Transmission Power Control

Adaptive transmission power control dynamically adjusts a node's transmission power based on transmission distance, link quality, or residual energy. In HWSNs, this technique allows low-energy nodes to manage power while enabling high-energy nodes to sustain robust links over longer distances. Such adaptability not only reducing unnecessary energy wastes but also minimizes interference and enhances overall network reliability (Lina Elmoiz Alatabani *et al.*, 2026).

4.4. Clustering-Based Communication Mechanisms

Clustering is one of the most extensively adopted communication techniques in HWSNs. In this method, sensor nodes are categorized into clusters, with CHs responsible for intra-cluster management, data aggregation, and inter-cluster communication. Heterogeneity is obviously leveraged by chosen energy-rich or high-capability nodes as CHs, thereby maximizing network lifetime, enhancing scalability, and minimizing communication overhead among ordinary nodes.

4.5.Cross-Layer Communication Approaches

Cross-layer transmission approaches break the conventional layered protocol design by allowing data exchange across numerous network layers. In HWSNs, parameters such as residual energy, channel conditions, and routing decisions can be jointly optimized to improve transmission efficiency. By enabling coordinated adaptation across the physical, MAC, and network layers, cross-layer designs provide critical energy savings and performance gains, albeit at the cost of increased design complexity.

5. ROUTING STRATEGIES FOR ENERGY EFFICIENCY IN HWSNS

Routing shows a pivotal role in shaping the energy efficiency and effective lifetime of HWSNs. Since data routing typically determines for the largest portion of node energy utilization, routing protocols must be cautiously designed to exploit node heterogeneity while mitigating communication overhead and load imbalance. This section briefly explains major routing strategies adopted in HWSNs, highlighting their energy-saving techniques, design trade-off, and applicability to diverse network scenarios (Potu Arayana *et al.*, 2026).

5.1. Flat Routing Protocols in HWSNs

Flat routing protocols consider all sensor nodes as equals and rely on data-centric or location-driven transmission rather than predefined roles. In HWSNs, flat routing is modified by allowing nodes with higher remaining energy or superior transmission capability to participate more actively in data routing. While this technique reduces the overhead connected to role assignment and cluster formation, it may result to excessive control traffic and limited scalability in large-scale networks. Flat routing is therefore more suitable for moderately sized HWSNs where node heterogeneity can be dynamically exploited without incurring significant coordination costs.

5.2. Hierarchical and Cluster-Based Routing Protocols

Hierarchical routing protocols structure HWSNs into clusters, with CHs responsible for packets aggregation and long-range transmission to the sink/BS. Energy efficiency is obtained by minimizing redundant transmissions and allocating energy-intensive tasks to high-energy or advanced nodes. Cluster-based routing efficiently balances energy utilization and improves scalability, making it one of the most extensively used strategies in HWSNs. However, frequent CH selection and maintenance may present overhead, particularly in highly dynamic or dense deployments.

5.3. Chain-Based and Tree-Based Routing Protocols

Chain-based routing protocols organize sensor nodes into linear chains, where data is sequentially routed/forwarded and aggregated before getting to the sink. This approach reduces long-distance communications and evenly distributes energy utilization among nodes. Tree-based routing protocols, in contrast, organize hierarchical packets forwarding approaches rooted at the sink, allowing efficient multi-hop transmission and data aggregation. In HWSNs, energy-rich nodes are frequently positioned closer to the sink or higher in the tree to assuage hotspot problems. Although these protocols provide improved energy efficiency, they may suffer from increased latency and minimized robustness to node failures.

5.4. Mobility-Aware Routing Strategies

Mobility-aware routing approaches are designed to address dynamic network conditions emanating from mobile sinks, mobile sensor nodes, or both. By modifying routes in response to topology changes, these protocols minimize transmission distance and prevent high energy depletion near static sinks. In HWSNs, mobility can be leveraged to redistribute traffic loads and maximize network lifetime. However, mobility-aware routing presents additional complexity in route management and may incur higher control overhead if not cautiously managed.

5.5. Comparative Discussion of Routing Approaches

Each routing approach introduces distinct benefits and limitations in terms of energy efficiency, scalability, and adaptability. Flat routing provides simplicity and flexibility but suffers with scalability. Hierarchical and cluster-based routing attained superior energy savings and load balancing, making it ideal for large-scale HWSNs. Chain-based and tree-based routing further minimize communication energy but may increase latency and sensitivity to node failures. Mobility-aware routing improves adaptability and hotspot management but at the cost of increased protocol complexity. Consequently, the selection of an energy-efficient routing approach in HWSNs should be guided by application requirements, network size, node heterogeneity, and mobility characteristics. Table 4 briefly describes the energy-efficient routing strategies in HWSNs.

Table 4: Comparative Summary of Energy-Efficient Routing Strategies in HWSNs

Ref.	Routing Strategy	Energy Efficiency	Scalability	Control overhead	Latency	Heterogeneity utilization	Typical Applications
Joanna Kulik et al., 2002	Flat routing	Moderate	Low-medium	High	Low	Limited (dynamic sharing)	Small-scale role monitoring
Yang Zhang et al., (2025)	Hierarchical/Cluster-based	High	High	Medium	Medium	High (energy-rich selection)	Large-scale CH sensing
Raghuveer Singh et al., (2025)	Chain-Based	Very High	Medium	Low	High	Moderate	Energy-critical deployments
Aart Sharma et al., (2025)	Tree-based	High	High	Medium	Medium	High (Relay placement)	Structured data collection
Abdulla Juwaied et al., (2025)	Mobility-aware	High	Medium-High	High	Low-medium	High (adaptive routing)	Mobile sink/node scenarios

6. ENERGY HARVESTING AND SUSTAINABLE HETEROGENEOUS WIRELESS SENSOR NETWORKS

Energy harvesting has developed a fundamental enabler for realizing long-term sustainability in HWSNs. Conventional battery-powered HWSNs are strictly constrained by limited energy reserves, which limit network lifetime and raise maintenance cost due to battery replacement. Energy harvesting presets the ability for sensor nodes to reload their energy from ambient environmental sources, thereby maximizing network operation and minimizing human intervention. In heterogeneous environments, nodes vary not only in hardware and energy capacity but also in harvesting ability, making energy harvesting a powerful balance to heterogeneity for creating self-sustaining and adaptive sensor networks (Bilal R. Al-Kaseem *et al.*, 2025).

6.1. Energy-Harvesting Models and Sources

Energy harvesting in HWSNs depicts the process by which sensor nodes transform external energy into usable electrical power. Common energy sources include “solar radiation, thermal gradients, mechanical vibrations (piezoelectric), wind energy, and radio-frequency (RF) signals”. Solar harvesting is the most extensively employed due to its relatively high energy density, while RF and vibration harvesting are predominantly attractive for indoor and industrial deployments (Yu Song *et al.*, 2025).

A commonly used energy-harvesting model represents the harvested energy at node i during a time interval t as:

$$E_h(i, t) = \eta_i P_s(i, t) \cdot t \quad (3)$$

Where $E_h(i, t)$ defines the harvested energy, η_i denotes the energy conversion efficiency of node i , and $P_s(i, t)$ depicts power available from the environmental source. The residual energy of a node is then updated as:

$$E_{res}(i, t + 1) = E_{res}(i, t) + E_h(i, t) - E_c(i, t) \quad (4)$$

Where $E_c(i, t)$ defines the energy utilization for sensing, processing, and communication. These models offer a mathematical basis for designing harvesting-aware protocols and evaluating sustainability performance.

6.2. Harvesting-Aware Communication and Routing

Harvesting-aware communication and routing schemes explicitly integrate energy harvesting dynamics into protocol design. Instead of depending solely on residual energy, routing decisions are prepared based on both current energy level and forecast harvested energy. Nodes with higher harvesting rates are chosen as CHs, relay nodes, or data aggregators, while energy-poor nodes function in low-duty or sleep modes. Such adaptive schemes allow enhanced load balancing, minimizing the risk of network sub-division, and optimize long-term stability by aligning communication tasks with energy availability.

6.3. Rechargeable and Hybrid Energy Storage Systems

To sustain harvested energy, sensor nodes are usually furnished with rechargeable batteries or super-capacitors. Rechargeable batteries offer higher energy density but experience limited charging cycles, whereas super-capacitors provide fast charging and maximize lifespan but minimize energy density. Hybrid energy storage schemes integrate both technologies, using super-capacitors for short-term buffering and batteries for long-term storage. In HWSNs, high-capability nodes usually use hybrid storage schemes to support energy-intensive operations, while low-end nodes depend on lightweight rechargeable units.

6.4. Challenges in Sustainable HWSNs

Despite their potential, viable HWSNs face numerous critical challenges. Energy harvesting is intrinsically unpredictable and recurrent, making reliable performance problematic to guarantee. Hardware cost and efficiency limitations limit large-scale deployment, mostly for RF and vibration harvesters. Moreover, harvesting-aware protocols proliferation system complexity and necessitate accurate energy prediction models. Other challenges comprise balancing fairness among nodes, managing heterogeneous harvesting rates, and guaranteeing reliable operation under changing

environmental conditions. Addressing these challenges remains a key research direction for the realization of fully autonomous and sustainable HWSNs.

7. CONCLUSION

This review has introduced a holistic examination of energy-efficient communication and routing strategies in Heterogeneous Wireless Sensor Networks, emphasizing how node diversity can be successfully exploited to improve network performance, scalability, and operational lifetime. By systematically scrutinizing communication mechanisms, routing protocols, and energy harvesting-based sustainability models, the review article has revealed that no single solution is universally optimal, and that protocol design must be steered by application requirements, network dynamics, and energy availability. The findings highlight the rising importance of harvesting-aware for sustainable HWSNs, while also showing insistent challenges related to scalability, complexity, and real-world deployment. Overall, this review offers a unified reference framework that can sustain informed protocol selection and inspire future research toward harvesting-aware reinforcement learning routing protocols, standardized heterogeneity metrics for fair protocol evaluation, public benchmark datasets for HWSNs routing comparison, Integration of machine learning with energy harvesting prediction, cross-layer optimization frameworks incorporating communication, routing, and energy management.

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