A Comprehensive taxonomical comparative analysis of Energy Harvesting Models for future trends

Dr Jaya Dipti Lal
Associate Professor, Electronics & Tc Department,
Shri G. S. Institute of Technology and Science, Indore, Madhya Pradesh, India.

Abstract: Energy harvesting has turned out to be a critical enabler for the sustainable deployment of the Internet of Things, which has the potential to run devices in a self-sustaining manner without battery replacement on a regular basis. This paper presents a detailed taxonomical survey pertaining to different energy harvester models from the statistical perspective, with emphasis on the advances and methodologies in use to enhance energy efficiency, network stability, and operational longevity of IoT systems. This includes implementations such as residual time-based energy harvesting schemes, clustering-based algorithms, advanced power management units, and bio-inspired optimization techniques. The review spreads into a broad range of implementations, such as in smart agriculture, environmental monitoring, wearables, and industrial IoT, with practical implementations and theoretical frameworks. Comparative analysis shows that the clustering-based BAT algorithm and improved smart energy-based routing protocol make huge contributions to network performance and stability, which makes it scalable for kinetic energy harvesting, while ViPSN- pluck and human footstep-based energy harvesting models. Aiming for this, edge computing and deep reinforcement learning were incorporated for the optimization of resource allocation and energy management. This paper reports a very nice overview of the state of the art in this field and at the same time outlines future research trends in search of energy harvesting solutions both adaptive and robust to the very dynamic requirements that IoT applications will surely have for different scenarios.

Keywords: Energy, Harvesting, Analysis, Scenarios, IoT, Models, Protocols

1. Introduction

The arrival of the IoT transformed many industries through its power to interconnect devices, systems, and services. This is an interoperable framework able to realize real-time data collection, analysis, and consequent decision-making, hence increasing efficiency, productivity, and user experience in most varied applications, including smart cities, industrial automation, healthcare, and environmental monitoring. However, one of the most important challenges that prevents IoT systems from widespread adoption and scalability is that all the distributed devices and deployments for IoT systems are heavily dependent on batteries. This results not only in extra maintenance costs due to frequent battery replacements and recharging but also leads to serious environmental concerns because of the disposal issues of batteries in different scenarios. EH has emerged as one of the solutions that can be used to counter these challenges by harnessing the ambient energy sources—solar, thermal, vibrational, and RF energy—in powering IoT devices and deployments. In this way, it shall be possible to establish self-maintaining and maintenance-free IoT systems, increasing operational life while reducing the environmental footprint of devices. Therefore, it is only if the efficiency and flexibility of energy harvesting models, developed for different scenarios in IoT applications, can be improved. In this paper, a detailed statistical taxonomy of various energy harvesting models is presented with the key focus on the development and methodologies adopted to attain better results in energy efficiency, network stability, and operational longevity in IoT. The review represents a high diversity of applications and includes practical implementations, together with theoretical frameworks developed in order to enhance the performance of energy harvesting systems.

One of the important models that would be discussed in this review is the residual time-based energy harvesting scheme, through which the RF charging signals are sent using the residual time in the communication slots. Such approaches lead to an enormous enhancement in energy harvesting and transmission rates, compared to the traditional systems that utilized the idle slots for RF charging. This model utilizes residual time to improve both energy efficiency and operational reliability in IoT networks, more so in the urban environment where transmission rate maximization and down-time minimization are of essence. Another very dominant model is that of the CBA-EH: Clustering-Based BAT Algorithm, where the Bat Optimization Algorithm is used for the optimization of clustering in energy harvesting-enabled sensor nodes. It significantly improves on stability, lifetime, and throughput of the network by optimizing the cluster head selection fitness factors. The triple sleeping strategy, introduced in this model, makes it predictable for simulating performance prior to IoT network deployment. Comparative analysis shows that TSS performs better than any other conventional sleeping strategy in terms of energy efficiency and prolonging the device's life since it maintains a higher mean battery level for a longer period. Other than the models, ISERP is described to enhance the power usage and life of the network by associating that with a WEH unit. ISERP can achieve good efficiency with respect to energy consumption compared to other routing techniques using hardware-based link quality estimation. The protocol will be very useful for distributed IoT frameworks to assure better energy efficiency and network lifetime. Another development of importance is related to storage-less energy harvesting and power management technique with MPPT. It achieves higher energy efficiency and a longer operational life compared to traditionally implemented on-chip energy harvesting systems. The effectiveness of the MPPT technique to enhance energy usage and operational life is validated by practical implementation experiences and theoretical analysis.

It has also reviewed one high-performance energy management unit, which uses a spark-switch tube and a buck converter for performance optimization of electrostatic generators. This model has huge improvement in power output and efficiency of IoT nodes, thus promoting practical applications of electrostatic nanogenerators in real applications. Another innovative model reviewed is the JSO-based Enhanced Energy Efficient LEACH protocol. This protocol uses a bio-inspired algorithm for clustering and monitoring energy, hence outperforming any traditional protocol in aspects of energy consumption and network throughput. This approach not only improves the quality of life by promoting sustainable agricultural practices but also helps in achieving ecological goals. It also introduces intelligent reflecting surfaces in beamforming optimization for energy harvesting. Improving wireless connectivity, signal strength, data rate, and coverage, IRS technology tremendously impacts energy harvesting system performance. In fact, the review of IRS hardware design and optimization methods underlines the potential of the technology in the future wireless networks. Notably, the review extends to the application of hybrid optimization algorithms, such as Hybrid Cuckoo Search Elephant Herding Optimization for Cognitive Radio Sensor Networks with energy harvesting. It is one of the routing protocols that enhances network performance and energy efficiency, hence ensuring reliable and energy-efficient data transmission.

Another practical and scalable solution reviewed was human footstep-based energy harvesting. Employing piezoelectric patches with simple circuits, the model is able to gather large amounts of power from human footsteps; it has feasible applications within public spaces and for health monitoring. It also brings into focus the application of fuzzy clustering and particle optimization in reducing energy consumption in the WSIoT network. The heuristic algorithms proposed efficiently manage energy in IoT networks and show good improvements in network throughput and energy consumptions. Conclusion: In this paper, there has been a complete review of different models of energy harvesting for IoT deployments. It goes on to describe the main features, performance metrics, and comparative advantages for every model. The variety of models underlines the huge potential of EH technologies in changing IoT systems into sustainable and maintenance-free operating styles. Future research should be oriented toward the refining of these models, enabling them to overcome the limitations pointed out and adapt to the evolving IoT applications.

2. Review of Existing Models used for Energy Harvesting Operations

Energy harvesting in IoT networks becomes a very vital area of research due to the ever-growing demand for sustainable and maintenance-free power solutions. The conventional devices powered by batteries normally have problems of limited life and frequent maintenance, hence developing the need for new techniques in energy harvesting. A lot of work has been dedicated to proposing several techniques and technologies for enhancing energy efficiency and network performance in IoT ecosystems. In the paper, the authors investigated the wireless power transfer in slotted ALOHA IoT networks. The authors have developed a new energy harvesting scheme that permits IoT devices, based on residual times, to scavenge energy during the residual time left over unused in a time slot. Compared with traditional methods when energy harvesting was done during idle slots only, the suggested approach significantly enhances the mean transmission rates of devices. Clustering algorithms have been used in enhancing the energy efficiency of IoT networks for a long time. In [2], the authors proposed the Clustering-Based BAT Algorithm for Energy Harvesting, CBA-EH, which makes use of the Bat Optimization Algorithm for optimizing the selection of a CH based on some factors of fitness like residual energy and inter-cluster distance. It demonstrated considerable improvement in the stability and lifetime of a network with substantial improvement compared to the GAOC protocol. Another line of research in [3] proposed eXtended Hybrid Petri nets to model the energy dynamics of smart IoT devices & deployments. This fluidic representation can be used to simulate continuous energy consumption and replenishment by renewable energy harvesting. They also introduced the Triple Sleeping Strategy, which optimizes energy conservation by keeping a higher mean battery level with respect to simpler sleeping strategies. Routing protocols can make a significant difference in increasing the lifetime and efficiency of IoT networks. In, it is proposed that ISERP integrates a wireless energy harvesting unit to extend the lifetime of the network with improvement in QoS. The protocol reduces 33% of the energy consumption in the cluster head and maintains 40% of the nodes active until the end of operational phases. Practical applications of energy harvesting techniques in real life are very important. In, the storage-less energy harvesting and power management technique using maximum power point tracking was introduced. This technique has higher efficiency in energy and longer operational delays, and is verified using both off-the-shelf components and on-chip fabrication. The electrostatic generators coupled with optimized energy management units were investigated in. In this work, the authors have developed an EMU that integrates a spark-switch tube with an RF inductor, significantly boosting the electrostatic nanogenerator's output power levels. The approach allows for a self-powered wireless temperature sensor node to transmit data continuously for different scenarios.

Reference	Method Used	Findings	Strengths	Limitations
[1]	Residual time-based energy harvesting scheme for slotted ALOHA in IoT networks	Demonstrated significantly higher mean transmission rates by utilizing residual time in time slots for RF	Increases energy harvesting and transmission rates effectively	Dependent on the specific slot time configurations

		charging signals		
[2]	Clustering-based BAT algorithm for energy harvesting in IoT-enabled wireless sensor networks	Enhanced network stability, lifetime, and throughput by 45%, 42.13%, and 48% respectively compared to GAOC protocol	Effective in managing operational costs and improving performance	Increased costs and reduced performance due to environmental factors
[3]	eXtended Hybrid Petri nets (xHPN) and Triple Sleeping Strategy (TSS)	TSS maintained a higher mean battery level by almost 8% over the double sleeping strategy	Predictive capabilities for simulating IoT network performance prior to deployment	Requires careful parameter selection and configuration
[4]	Improved Smart Energy-Based Routing Protocol (ISERP) combined with wireless energy harvesting (WEH)	Reduced energy consumption in CHs by 33% and kept 40% of nodes active until the end of phases	Enhances network longevity and QoS under high congestion	Requires accurate cost function estimation for CH and CG selection
[5]	Storage-less energy harvesting and power management technique with maximum power point tracking (MPPT)	Achieved higher energy efficiency and longer operation times than traditional energy harvesting systems	Practical and efficient for small form-factor and maintenance-free IoT devices	Initial implementation requires off-the-shelf components and on-chip fabrication
[6]	High-performance energy management unit (EMU) for electrostatic generators	Improved power output of rotary electret generators by 1.2 times and triboelectric nanogenerators by 1.5 times	Promotes practical applications of electrostatic nanogenerators in IoT nodes	High impedance mismatch with electronics limits energy utilization efficiency
[7]	JSO-based Enhanced Energy Efficient LEACH (JSO-LEACH) Protocol	Achieved better performance in terms of energy consumption, packet delivery ratio, and network stability	Effective in optimizing energy usage and extending the stability period	Complexity in clustering and routing calculations

[8]	Review on renewable energy harvesting in precision agriculture	Highlighted potential for sustainable health surveillance systems and precision agriculture using renewable energy sources	Comprehensive review of applications and energy consumption issues in IoT	Limited to review and lacks implementation details
[9]	Review of intelligent reflecting surfaces (IRS) for energy harvesting	Enhanced wireless connectivity, signal strength, data rate, and coverage with IRS technology	Extensive comparative analysis and optimization methods for IRS-assisted energy harvesting	Faces substantial research challenges in optimization and practical deployment
[10]	Hybrid Cuckoo Search Elephant Herding Optimization (HCSEHO) for CRSN routing protocol	Improved energy efficiency and reliable medical data transmission	Effective in extending network lifetime and optimizing energy harvesting	Complexity in hybrid optimization algorithm implementation
[11]	Footstep-based energy harvesting floor tile	Successfully generated 246 mW of power to illuminate two LEDs with a cost-effective prototype	Potential for widespread deployment in high-traffic areas	Limited power generation and scalability issues
[12]	Fuzzy clustering and particle optimization in WSIoT networks	Demonstrated 9.57% improvement in network throughput and 8.47% reduction in energy consumption	Synergy of fuzzy clustering and particle optimization for energy-efficient IoT networks	Complexity in algorithm implementation and simulation
[13]	Review of IoT-based energy-efficient routing protocols for smart agriculture	Provided insights into various protocols enhancing productivity and energy efficiency in agriculture	Guidance for researchers to contribute to energy-efficient agricultural practices	Limited to review and lacks experimental validation
[14]	IoT Heterogeneous	Achieved 90%	Comprehensive	Dependent on

	Energy Harvesting (IHEH) technique for smart home energy management	efficiency per day, yielding more power and increasing battery lifetime	energy management for residential IoT devices	heterogeneous energy sources and scheduling accuracy
[15]	Energy-aware task scheduler for batteryless IoT devices	Ensured successful execution of application tasks and maintained forward progress despite power failures	Effective in adapting to environmental changes and avoiding power failures	Dependent on accurate voltage threshold definitions for tasks
[16]	Feasibility evaluation approach for batteryless IoT devices	Modeled worst-case energy consumption periods, ensuring IoT devices can be powered by energy harvesters	Simplifies characterization of energy consumption for wireless technologies	Requires precise power measurements and PMU configurations
[17]	Runtime energy-allocation framework with rollout algorithm	Achieved up to 35% higher utility under energy-limited scenarios with minimal energy overhead	Optimizes energy utilization and compensates for deviations in energy harvesting patterns	Complexity in algorithm implementation and energy allocation corrections
[18]	Optimal Transmit Power and PS Ratio (OTPR) algorithm for SWIPT	Improved energy efficiency and minimized co-channel interference with DNN training	Effective in optimizing resource allocation for IoT devices	Complexity in DNN training and algorithm implementation
[19]	Energy-efficient routing technique for IoT-based WSNs	Enhanced network longevity and successful routing with efficient link selection	Simple and effective in reducing energy consumption of IoT nodes	Limited to specific routing scenarios and may require further optimization
[20]	Practical Power-Aware Algorithm for Solar Sensors (PPAASS)	Maintained higher average duty cycle and quick adaptation to energy harvesting prediction failures	Ideal for constant monitoring applications with real-time duty cycle adaptation	Dependent on accurate solar irradiance predictions and battery backup levels

Table 1. Review of Existing Methods

Bio-inspired algorithms have proved quite promising to optimize energy consumption for IoT-based networks. Reference [7] proposed an enhanced energy-efficient LEACH protocol based on JSO, and an optimization algorithm was bio-inspired to establish efficient clustering of the nodes by distance. This resulted in more gainful performance in consuming energy, packet delivery ratio, and enablement of the overall stability of networks. Applications of renewable energy harvesting in precision agriculture are reviewed in [8]. There, the group discussed the deployment of quite sustainable energy solutions to enhance agricultural production and achieve ecological objectives, including the likes of solar, vibration, thermal, and ambient radio frequency sources. Intelligent Reflecting Surfaces (IRS) have also received much attention lately in optimizing energy harvesting within IoT networks. Within a wide-ranging review, [9] addressed many beamforming optimization strategies with practical prototypes regarding in-field IRS. Such results were promising as it suggested IRS technology deployment to increase wireless connectivity and enhanced energy efficiency. In [10], the routing design was provided by the authors with a newly designed HCSEHO algorithm that already combines Cuckoo Search Infrastructure with Elephant Herding Optimization for proposing a new solution for the Routing Protocol for the Cognitive Radio Sensor Networks. It integrated the two processes of energy harvesting and path routing within the design for extending the network lifetime and always reliably providing the energy-efficient data routing. In [11] the human footsteps are seen as a source of kinetic energy. One demonstration floor tile was able to convert footsteps of human beings into something useful, for example, electric power, something that provides an environmentally friendly alternative to the conventional power sources. That is something likely to radiate from the high-traffic sources like railway stations and the streets. A new methodology, it combines fuzzy clustering with particle optimization, to tackle energy challenges in WSiOT networks, as shown in [12]. The presented scheme yielded remarkable gains in throughput and network energy efficiency when benchmarked with existing schemes. The work in [13] surveyed the routing protocols for efficient energy in smart agriculture. It established some protocols like MAC, cross-layer, LEACH, and AI-based methods and their roles in increasing agricultural productivity and operational efficiency. In [14]: IoT for integrating home appliances towards energy harvesting. The proposed technique is called IoT Heterogeneous Energy Harvesting that is used for tracking and distributing different kinds of energy, reaching 90% efficiency each day. This approach enhances the lifetime of batteries in smart home systems efficiently. The scheduling of tasks in batteryless IoT devices has to be efficient to deal with intermittent power availability. In [15], an energy-aware task scheduler that enables an intelligent schedule of application tasks according to their dependencies and priorities to ensure their successful execution despite power failures is presented. In [16], the feasibility evaluation approach focuses on modeling a worst-case scenario, that is, with peak energy consumption. This is to help in determining if IoT devices could be successfully available in the future when energy harvesters would drive them, particularly at periods when there is energy demand. Harvested energy forecast is virtually impossible to achieve due to uncertainty. The energyallocation runtime framework developed in [17] optimizes the energy in consideration. It discusses the state of the intent rollout algorithm, which significantly boosts utility under energy-limited circumstances. The work in [18] proposed new kinds of resource allocation schemes that could achieve maximal harvested energy while achieving an increase in efficiency in terms of energy within the IoT network. The OTPR algorithm yielded excellent energy efficiency and transmission power control in PS ratio management for optimum transmit power. It is a critical module of energy management for solar-powered devices for its functioning. In [20], a PPAASS algorithm is given with a duty cycle that is set expeditiously based on battery levels and solar irradiance predictions in order to maintain usage of harvested energy with high preservation of power availability. In the study by [21], the potentials of soil-air thermal energy harvesting were explored using a custom-made SoTEG.

This system demonstrated to have a heat transfer efficiency = 34.5%, and it is able to generate 110 μW of power at 3°C of temperature difference. The experiments also demonstrated that the energy harvesting was weather-dependent, in which solar radiation positively impacts the harvested energy and wind conditions have variable impacts on the harvested energy. Work by [22] presented a privacy aware energy harvesting scheme for 6G-enabled IoT. The system in [23] includes the ViPSN-pluck system with a structure of piezo-magneto-elastic to collect energy from transient motions. This durable design ensures energy harvesting reliability and efficient motion detection with communication over Bluetooth Low Energy. The cyber-electromechanical synergy between the components underlies at a primal level the robustness of this system with respect to the solar and RF energy harvesters, which are perpetually susceptible to outages of energy. Authors in [24] provided the Sustainability in Dominating Set scheme for IoT networks enabled with solar energy harvesting. The new SID scheme maintains a CDS based on the nodes' energy levels, whereby implementation and simulation results showed that it significantly improves residual energy, message complexity, and CDS size relative to the traditional methods, thereby proving its feasibility in maintaining sustainable IoT networks. Reference [25] investigates using microwave power transfer for wireless energy harvesting in IoT devices and deployments. In this work, a scalable rectenna design for dynamic power harvesting throughout continuous variation and robust, orientation-insensitive operation is presented. WEH system with flexible assembly configurations effective in numerous scenarios. A triple-mode DC-DC converter for energy harvesters in IoT edge nodes was reported in [26]. The regulator implemented in 0.18-μm CMOS technology achieved a maximum efficiency of 88.7% over a wide input range of 1.2 to 4V and output range of 1 to 4V. The load transient response and steady performance of the converter are in good agreement and find application in energy harvesting in IoT systems, which must be supported from a number of energy sources. An extensive study by [27] quantified the energy harvesting potential from human activity based on over 67,000 users. The obtained results indicated that energy harvesting potential differed highly depending on age, activity, and medical conditions, such as diabetes. This study highlights how difficult it can be to achieve wearable IoT device energy autonomy for health monitoring. Integration with Edge Computing technology and Energy Harvesting was considered in [28]. The proposed REP-DRL algorithm applies deep reinforcement learning for renewable energy prediction and offloading decision optimization. The simulation results illustrated that the system could adapt to various conditions toward fostering energy sustainability and increasing processing efficiency for IoT devices and their deployments.

Reference	**Method Used**	**Findings**	**Strengths**	**Limitations**
[21]	Soil-air Thermoelectric Generator (SoTEG)	Demonstrated heat transfer efficiency of 34.5%, generating power from temperature differences as low as 3°C	Effective in low-temperature differences; detailed design and simulation analysis	Limited by weather conditions; potential for improvement in heat transfer efficiency
[22]	Differential privacy and intelligent reflecting surface for 6G-enabled IoT	Developed a secure, intelligent energy harvesting framework with enhanced privacy and user	High privacy preservation and user satisfaction through deep reinforcement learning	Complexity in implementing differential privacy mechanisms and IRS technology

		satisfaction		
[23]	ViPSN-pluck (vibration-powered sensing node with plucking-motion energy harvester)	High reliability in energy harvesting and effective motion detection and BLE communication	Robust design, cyber-electromechanical synergy, high energy reliability	Limited by specific use-case scenarios; comparison with solar and RF energy harvesting not provided
[24]	Sustainability in Dominating Set (SID)	Improved residual energy by up to 25.6%, reduced message complexity by up to 88.5%, and reduced CDS size by up to 54.5%	Effective energy management, reduced message complexity, sustainable CDS maintenance	Dependent on cloud cover and environmental conditions; complexity in approximation algorithm
[25]	Microwave power transfer using scalable rectenna design	Adapted to diverse power requirements, demonstrated scalable and orientation-insensitive energy harvesting	Scalable design, high-gain endfire radiation pattern, effective for dynamic power harvesting	Challenges with polarization and orientation mismatch; redesign requirements for different demands
[26]	Triple-mode DC-DC converter for IoT edge nodes	Achieved peak efficiency of 88.7% with a wide input range and load transient response time of <450 µs	High efficiency, stable operation, suitable for varying energy sources	Requires specific CMOS process fabrication; complexity in automatic buck-boost operation
[27]	Kinetic energy harvester model using UK Biobank data	Identified key differences in power output based on participant age, activity, and medical conditions	Largest study on energy harvesting from human motion; high temporal resolution data	Lower energy harvesting potential in older participants and those with medical conditions like diabetes
[28]	Deep Reinforcement Learning (REP-DRL) for energy sustainability in	Improved energy sustainability and extended battery life by optimizing service offloading	Adaptable to varying conditions, optimized resource utilization	Dependent on accurate RE predictions; complexity in implementing deep

	IoT	decisions		reinforcement learning algorithms
[29]	Opportunistic Backscatter communication Medium access control (OBM) protocol	Improved network throughput and energy efficiency for heterogeneous wireless energy harvesting IoT networks	Effective in managing collisions and interference, smooth communication for backscatter tags	Complexity in contention and communication techniques; potential interference issues
[30]	Energy harvesting modulation (EHM) scheme for IIoT	Optimized ICSET performance, increased effective control rate while ensuring energy harvesting performance	Theoretical validation, effective control reliability, and energy harvesting	Requires precise time slot selection; complexity in integrated control state and energy transfer
[31]	Dual-purpose radial-array rectenna for RF energy harvesting and orientation sensing	Achieved improved tolerance for angular misalignment and orientation-oblivious energy harvesting	Dual-purpose design, high orientation estimation accuracy, stable energy harvesting	Limited to specific RF frequency; potential complexity in calibration and MMSE method
[32]	Miniaturized RF energy harvester with dual-polarized antennas	Achieved 71.4% conversion efficiency and harvested 1.6 times more power from ambient RF signals	Compact design, improved power harvesting, effective for various incident angles	Dependent on specific ISM frequency band; potential limitations in power output for very low energy environments
[33]	Imitation Learning (IL)-based energy management algorithm	Achieved near-optimal energy allocation with minimal overhead, effective for long-term recharge-free operation	Low energy consumption overhead, effective solar EH data utilization	Dependent on accurate Oracle policy design; complexity in training and implementation
[34]	On-silicon inductor coil with integrated buck	Achieved a maximum efficiency of 69.1%	High inductance, simple CMOS technique, effective	Limited to specific low-power IoT applications;

	DC-DC converter	at 30 MHz for low-power IoT scenarios	for energy harvesting scenarios	potential challenges in integration and scalability
[35]	Monte-Carlo ray-tracing simulation for Organic Photovoltaics (OPV)	Validated OPV model for indoor energy harvesting and SLIPT scenarios, effective for IoT nodes	First model of its kind, suited for indoor applications, high validation accuracy	Complexity in numerical approaches; limited to indoor environments and specific IoT nodes
[36]	Overview of RF energy harvesting and wireless power transmission (WPT) technologies	Discussed advancements in flexible rectennas, SWIPT, and 5G millimeter wave power	Comprehensive historical overview, identification of main challenges and recent advances	General overview, lacks specific experimental validation for new advancements
[37]	Lyapunov-chain offloading algorithm for UAV-based edge computing	Maintained strong energy stability, minimized execution delay compared to baseline schemes	Robust energy stability, effective for various scenarios, theoretical validation	Complexity in Lyapunov function construction; dependent on UAV cluster efficiency
[38]	Quad-band energy harvester (QBEH) with E-CRLH TLs	Achieved overall efficiency of 55%-70%, effective for low-powered sensors and IoT devices	High efficiency, sensitivity improvement, broad input power range	Complexity in E-CRLH TLs design; dependent on accurate theoretical analyses and Volterra series
[39]	Active and passive integrated Reconfigurable Intelligent Surfaces (RIS)	Enhanced IoT system performance, optimized signal reflection and transmission	Synergism of active and passive components, advanced optimization mechanism	Complexity in mixed-integer nonlinear programming; dependent on accurate channel gain models
[40]	Vibration-powered LoRaWAN-based sensor node for IIoT	Ensured continuous operation with effective energy harvesting from vibrations	Effective for hard-to-reach positions, high efficiency in energy regulation	Dependent on specific vibration sources; potential challenges in sensor sampling

				rate optimization

Table 2. Review of Existing Methods

Results from a study in [29] have also shown heterogeneous wireless energy harvesting IoT networks, using an Opportunistic Backscatter Medium access protocol for the channel communication, termed the OBM protocol. This vision will involve a way to manage collisions and interferences between the selection of wireless data and energy transmissions—a way to improve network throughput and energy efficiency, marking the effectiveness of backscatter communication in energy-constrained environments. Ref. [30] proposed an EHM scheme for ICSET in IIoT. This scheme provides WET optimization with control state delivery for control reliability and energy harvesting performance. Results from simulations support the theoretical analysis and prove that the EHM scheme is effective in IIoT scenarios. In [31], a dual-use radial-array rectenna architecture was proposed for RF energy harvesting and orientation sensing in IoT nodes. The proposed architecture has eight rectenna elements to improve tolerance to angular misalignment and consequently further stabilize energy harvesting. Experimental results showed very low estimation error of orientation and improved energy harvesting performance as compared to single rectenna architectures. Ref. Equipped with a two-layer PCB substrate and a pair of orthogonal antennas, the harvester demonstrations integrated a Dickson charge pump circuit and produced a conversion efficiency measured at 71.4%, showing an increment in power-harvested throughput from ambient RF signals. The compact design can be put to use in ultra-low-power IoT sensors and medical applications. Reference [33] presented an imitation learning-based energy management algorithm for IoT devices without dynamic optimization. The IL algorithm trained with Oracle policies ran near-optimally in energy allocation with minimum overhead. Experiments on solar EH data validated this approach in showing the effectiveness with low power in the approach. Work in [34] targeted a piece of embedded hardware: this study evaluated the performance of an on-silicon inductor coil integrated with a buck DC–DC converter fabricated in a 180 nm CMOS process. The inductor achieved stable values over a wide frequency range, while the converter reached an overall peak efficiency of approximately 69.1%. This integration gives a great ability to manage electricity in energy harvesting scenarios.

The application of OPVs for indoor energy harvesting in IoT scenarios was evidenced in. The work validated an OPV model for harvesting energy and receiving optical data in a SLIPT scenario, through Monte Carlo ray-tracing simulations. The results confirmed that the use of OPVs would be suitable to power low-power IoT nodes in indoor scenarios. A comprehensive review of the RF EH and RF WPT technologies can be found in [36]. Technical challenges, recent progresses, and possible applications of the RF EH and RF WPT, including the case of powering the RFID systems via 5G networks, are argued in the paper. The most dynamic evolvements in rectenna flexible designs and SWIPT are clarified for future lowpower wireless systems. The research in [37], through the adaptation, introduced a new model to use UAV clusters with energy-harvesting capability for computational offloading in edge computing. There is a proposed Lyapunov-chain offloading algorithm to guarantee energy stability with respect to delay expenditure. Simulation results show the algorithm is robust and efficient in achieving stable energy states and providing reliable computational service. A quad-band energy harvester (QBEH) based on extended composite right- and left-handed transmission lines (E-CRLH TLs) was reported in [38]. The QBEH, operating at four frequency bands, demonstrated high efficiency and sensitivity, making it ideal for harvesting ambient RF energy in urban environments. The theoretical and experimental results have validated the work to be effective for deployments of low-power IoT devices. In [39], authors suggested a technique for enhancement of the IoT communication using active and passive functionality-enabled RIS. The work presented developed optimization mechanisms allowing the signals to be reflected and transmitted in manners that improve system performance but still achieve energy efficiency. The simulation analysis confirmed the superiority of RIS panels in the optimization of IoT system performance over traditional methods. It has been discussed whether possible energy sources for wireless-sensing platforms for the IIoT could be vibrations [40]. In that definition, vibrating machinery is outfitted with piezoelectric sensors to realize energy self-sufficiency of the platforms. Results have shown that the optimization of the energy availability and the sensor's sampling rate can guarantee the continuous operation of devices and deployments. This literature review summarizes the taxonomical analysis about various energy harvesting models in the IoT networks from a statistical perspective. The advanced techniques and integration approaches discussed, right from thermal and motion energy harvesting to advanced algorithms, have shown high advancement within this decade. These studies contribute to the development of energy efficiency, sustainability, and performance for IoT networks and, therefore, provide a stepping stone toward further research and development in energy harvesting technologies.

3. Taxonomical Comparative Analysis

This section is a comprehensive taxonomy of the various EH methodologies for IoT systems. The overall categorization of EH methodologies can broadly be divided: algorithm-based optimization, hardware-oriented techniques, and application-specific strategies. Algorithm-based optimization techniques include CBA-EH, which corresponds to the Clustering-based BAT Algorithm, and JSO-LEACH Protocol for JSO-based Enhanced Energy Efficient LEACH. These advanced computational methods strive to achieve better energy efficiency and improved network performance. For instance, CBA-EH exploits the BAT algorithm to attain optimal clustering with EH-enabled sensor nodes, which showed tremendous improvements in the stability, lifetime, and throughput of the network. Second, JSO-LEACH uses bio-inspired algorithms to achieve energy management and enhance the packet delivery ratio, hence proving the efficiency of heuristic algorithms concerning energy management for IoT networks. On the hardware side, many studies are targeted at developing efficient energy management units and converters in order to raise the energy harvesting capacity and utilization. Herein, it presents the high-performance energy management unit as an integration of a spark-switch tube and a buck converter. This supplied a boost of 1.2–1.5 times additional power output over systems without an EMU. Other examples of hardware improvements are given by the miniaturized RF energy harvester and the triple-mode DC-DC converter; the former has recently achieved conversion efficiency of 71.4% by using dual-polarized antennas, and the latter is capable of showing peak efficiency of 88.7% due to its effective method for energy conversion. All these hardware-focused approaches are very vital in enhancing EH system practical deployment within IoT environments, thus offering robust and effective energy capture and utilization.

Another critical dimension of EH methodologies is application-specific strategies, tailored to meet the particular energy demand and constraints of a given IoT application. Renewable energy harvesting for precision agriculture emphasizes the use of EH technologies in farming to improve farm productivity and operational efficiency. Such a scheme does not only help in energy sustainability but also enriches life quality through the enablement of smart farming solutions. Another example of EH technologies applied in environmental and industrial settings can be seen through the Soil-air Thermoelectric Generator and the Vibration-powered IoT Sensing Platforms. SoTEG efficiently generates power by exploiting temperature differences, whereas the vibration-powered platform enables uninterrupted operation of industrial IoT applications through piezoelectric sensors. These strategies put forth the flexibility of EH methodologies in solving different application-specific energy needs. The comparative analysis with respect to different EH methodologies shows considerable progress and diversified approaches toward optimizing energy efficiency and network performance of IoT systems. For example, the Improved Smart Energy-Based Routing Protocol itself decreases 33% of the energy consumption by Cluster Heads and keeps 40% of nodes active till the end of phases, thus turning out to be better in energy management and network longevity as compared to any existing routing algorithm. In contrast, Runtime Energy-allocation Framework and IL-based Energy Management Algorithm take into account device utility and energy allocation to ensure an improvement in utility by about 35% and close-to-optimal energy allocation, respectively. The methodologies underline how important adaptive, intelligent solutions are to energy management for sustainability in IoT device operations under severe energy constraints.

Paper	Method	Key Features	Performance Metrics	Comparative Analysis
[1]	Residual Time Based Energy Harvesting Scheme	Utilizes residual time in slots for RF charging; increases energy harvesting and transmission rates	Higher mean transmission rates compared to idle slot-only systems	Residual time usage boosts energy efficiency and transmission rate significantly
[2]	Clustering-based BAT Algorithm (CBA-EH)	Optimizes clustering with BAT algorithm for EH-enabled sensor nodes	Improves network stability, lifetime, and throughput by 45%, 42.13%, and 48% respectively compared to GAOC protocol	Effective clustering and optimization enhance network performance
[3]	Extended Hybrid Petri Nets (xHPN)	Fluidic representation models battery behavior; introduces Triple Sleeping Strategy (TSS)	Maintains mean battery level 8% higher than double sleeping strategy with 90% sleeping percentage	TSS outperforms traditional sleeping strategies in energy efficiency
[4]	Improved Smart Energy-Based Routing Protocol (ISERP)	Enhances power usage and network lifespan with WEH unit	CHs use 33% less energy; 40% of nodes remain active until end of phases	Superior energy efficiency and network longevity compared to existing routing algorithms
[5]	Storage-less EH and Power Management with MPPT	On-chip implementation for maximum power tracking	Higher energy efficiency and longer operation time than traditional systems	Effective MPPT technique enhances energy utilization and operational longevity
[6]	High-Performance	Uses spark-switch	Maximum power	Significant

	Energy Management Unit (EMU)	tube and buck converter for optimization	output 1.2-1.5 times higher than without EMU	improvement in power output and efficiency for IoT nodes
[7]	JSO-based Enhanced Energy Efficient LEACH (JSO-LEACH) Protocol	Uses bio-inspired algorithm for clustering and energy monitoring	Consumes 24.6686 J on average; 66.5538% packet delivery ratio	JSO-LEACH achieves better performance in energy consumption and network throughput
[8]	Renewable Energy Harvesting for Precision Agriculture	Reviews application of renewable EH in agriculture	Enhances productivity and operational efficiency	Sustainable agriculture practices with IoT integration improve quality of life
[9]	IRS-assisted Beamforming Optimization	IRS hardware design and optimization for EH	Improves data rate, coverage, and signal strength	Beamforming strategies significantly enhance IRS performance in EH
[10]	Hybrid Cuckoo Search Elephant Herding Optimization (HCSEHO)	Routing protocol for CRSN with EH	Enhances network performance and energy efficiency	Optimal path selection ensures reliable and energy-efficient data transmission
[11]	Human Footstep-based Energy Harvesting	Uses piezoelectric patches and simple circuits	Generates 246 mW power; cost-effective	Demonstrates practical and scalable EH solution for public spaces
[12]	Fuzzy Clustering and Particle Optimization	Reduces energy consumption in WSIoT networks	9.57% improvement in throughput; 8.47% reduction in energy consumption	Heuristic algorithms effectively manage energy in IoT networks
[13]	IoT-based Energy-efficient Routing in Smart Agriculture	Reviews various routing protocols for smart farming	Increases productivity and energy efficiency	Guides future research in energy-efficient agricultural IoT

				systems
[14]	IoT Heterogeneous Energy Harvesting (IHEH) Technique	Manages energy for smart home appliances	Achieves 90% efficiency per day	Effective energy distribution and management for smart homes
[15]	Energy-aware Task Scheduler	Schedules tasks for batteryless IoT devices	Ensures safe execution; adapts to environmental changes	Maintains device operation and task execution without power failures
[16]	Feasibility Evaluation Approach for IoT Technologies	Models worst-case energy consumption periods	Simplifies characterization for sustainable IoT operation	Provides reliable assessment of IoT technologies under peak conditions
[17]	Runtime Energy-allocation Framework	Optimizes device utility under energy constraints	Achieves up to 35% higher utility	Efficient energy management ensures continuous device operation
[18]	SWIPT with Optimal Transmit Power and PS Ratio (OTPR)	Jointly optimizes channel, PS, and power control	Improves EE and minimizes training time	DNN training enhances performance and reduces energy overhead
[19]	Energy-efficient Routing with EH Techniques	Proposes simple routing technique for IoT-based WSNs	Improves network longevity and energy utilization	EH techniques enhance routing efficiency and network performance
[20]	Practical Power-Aware Algorithm for Solar Sensors (PPAASS)	Adapts duty cycle based on energy predictions	Maintains higher average duty cycle	Real-time adaptation maximizes use of harvested energy
[21]	Soil-air Thermoelectric Generator (SoTEG)	Harvests energy from temperature differences	Generates 337 μW power at 2.75°C difference	Efficient design for environmental energy harvesting
[22]	Privacy-preserving Energy Harvesting	Uses IRS and differential privacy	Maximizes user satisfaction and	Ensures privacy and efficiency in

	for 6G IoT	for secure EH	resource allocation	energy harvesting for 6G networks
[23]	ViPSN-pluck for Transient-motion Energy Harvesting	Uses piezo-magneto-elastic structure	Efficiently harvests and utilizes motion energy	Reliable and robust EH solution for IoT motion detection
[24]	Sustainability in Dominating Set (SID)	Constructs adaptive CDS for EH-enabled IoT networks	Saves 14.3% energy; reduces message complexity by 88.5%	Enhances network sustainability and efficiency with CDS approach
[25]	Scalable RF Battery for Microwave Power Transfer	Uses plug-in-type rectenna cells	Adapts to user requirements; high-gain radiation pattern	Scalable design for dynamic power harvesting in IoT networks
[26]	Triple-mode DC-DC Converter for EH	Demonstrates MPPT and efficient energy conversion	Peak efficiency of 88.7%; load transient response <450 µs	High efficiency and stability for IoT edge nodes
[27]	Energy Harvesting from Human Motion	Uses accelerometry data to estimate EH potential	Identifies age and condition impacts on EH output	Large-scale study highlights challenges in wearable IoT EH
[28]	REP-DRL for Edge Computing with EH	Uses deep reinforcement learning for RE predictions	Optimizes service offloading and energy sustainability	Adapts to varying conditions and optimizes resource utilization
[29]	OBM Protocol for Heterogeneous Wireless EH Networks	Enables smooth backscatter communication	Improves network throughput and energy efficiency	Effective protocol for heterogeneous IoT networks
[30]	EHM Scheme for IIoT	Integrates control state and energy transfer	Optimizes control reliability and EH performance	Enhances efficiency and reliability in IIoT scenarios
[31]	Dual-purpose Radial-array Rectenna	Provides orientation sensing and RF energy harvesting	Achieves high efficiency and low estimation error	Innovative design for efficient and robust EH in IoT nodes

[32]	Miniaturized RF Energy Harvester	Uses dual-polarized antenna and Dickson charge pump circuits	71.4% conversion efficiency	Compact and efficient design for ambient RF EH
[33]	IL-based Energy Management Algorithm	Uses Oracle policies for energy allocation	Achieves near-optimal energy allocation	Low energy overhead and high efficiency for IoT devices
[34]	On-silicon Inductor Coil with DC-DC Converter	Uses CMOS process for integrated inductors	Maximum efficiency of 69.1% at 30 MHz	High potential for energy management in EH scenarios
[35]	Organic Photovoltaics for Indoor EH	Uses Monte-Carlo simulation for optical power	Suitable for indoor EH and data reception	Innovative approach for low-power IoT nodes
[36]	RF Energy Harvesting and WPT Technologies	Discusses historical overview and technical challenges	Trends in flexible rectennas and SWIPT	Future outlook on RF EH and WPT systems
[37]	UAV-based Computational Offloading with EH	Uses Lyapunov-chain offloading algorithm	Maintains strong energy stability and minimizes delay	Robust and efficient computational offloading for UAVs
[38]	Quad-band Energy Harvester (QBEH)	Uses E-CRLH TLs for matching network	55-70% efficiency; wide input power range	Practical solution for ambient RF EH in urban environments
[39]	RIS for IoT System Enhancement	Combines active and passive RIS functionalities	Optimizes signal reflection and transmission	Enhances IoT system performance with RIS technology
[40]	Vibration-powered IoT Sensing Platforms	Uses piezoelectric sensors for vibration EH	Continuous operation with optimized sensor sampling rates	Effective EH for industrial IoT applications

Table 3. Taxonomical Review of Existing Methods

Advanced techniques include Human Foot Step Based Energy Harvesting and Hybrid Cuckoo Search Elephant Herding Optimization, which are further illustrative of the integration of EH technologies with natural and bio-inspired. Human Foot Step Based EH harnesses power generated using footsteps through piezoelectric patches and is low cost and scalable for public spaces. On the other hand, the HCSEHO algorithm uses hybrid techniques to provide reliable and energy-efficient data transmission using cognitive radio sensor networks. These are methodologies that underline the creative inclusion of the technologies based on EH into the routine of actions and natural events, thereby forming the perspectives of new peculiarities of sustainable energy solutions in systems related to the IoT. It also raised the need for privacy and security in recent IoT systems based on 6G advanced networking. The privacy-preserving energy harvesting for 6G IoT integrates the use of an intelligent reflecting surface and differential privacy techniques to ensure secure energy harvesting while achieving at most levels of user satisfaction and resource allocation. This is very necessary because in IoT networks, data privacy and security concerns are increasingly changing; hence, EH technologies can be rolled out without jeopardizing levels of trust by the users and data integrity. In taxonomic analysis, EH methodologies in IoT systems offer a heterogeneous landscape of innovative techniques to enhance energy efficiency, network performance, and application-specific requirements. The three main pillars for these methodologies are: algorithm-based optimization, hardware-related means, and application-specific strategies, each bringing some unique contributions to achieving the overall goal of long-term energy sustainability in IoT settings. These methodologies have, therefore, achieved high improvements that can be underscored through a comparative analysis. The methodologies do realize the critical role adaptive, intelligent, and secure solutions have to play in the future of IoT systems. The place of advanced EH technologies is, therefore, going to be very important to ensure the sustainability and efficiency of such pervasive networks as IoT continues to expand into the future.

4. Statistical Comparative Result Analysis

The next analysis is a comparison of the methods applied in energy harvesting, considering some key performance metrics about the efficiency of energy harvesting, numerical results, and some specific observations on energy harvesting. This comparison gives a very fine view of each method applied in EH—both its strengths and weaknesses—thus allowing understanding regarding real-life applications and further improvement operations.

Reference	**Method Used**	**Results (In Numerical Form)**	**Efficiency of Energy Harvesting**	**Observations in terms of Energy Harvesting**
[1]	Residual time-based energy harvesting scheme	Significantly higher mean transmission rates	High efficiency in utilizing residual time	Effectively increases transmission rates, optimizes unused time slots
[2]	Clustering-based BAT algorithm for energy harvesting (CBA-EH)	Improved stability by 45%, network lifetime by 42.13%, throughput by 48%	Efficient in optimizing cluster head selection	Effective in enhancing network stability and reducing operational costs
[3]	eXtended Hybrid	90% sleeping	High energy	Efficient in

	Petri nets (xHPN) and Triple Sleeping Strategy (TSS)	percentage maintains mean battery level 8% higher than double sleeping strategy	efficiency, better battery management	conserving energy, predictive capabilities for IoT networks
[4]	Improved Smart Energy-Based Routing Protocol (ISERP)	CHs use 33% less energy, 40% of nodes remain active until the end	High energy efficiency, extended network lifespan	Reduces control overhead, enhances network quality of services
[5]	Storage-less energy harvesting and MPPT power management	Higher energy efficiency and longer operation time	High efficiency with duty-controlled method	Practical for small form-factor and maintenance-free IoT devices
[6]	Electrostatic generator with high-performance energy management unit (EMU)	Maximum power of 79.2 mW m-2 rps-1, 1.5 times higher power output with EMU	Highly efficient energy utilization	Promotes utilization of electrostatic nanogenerators in IoT nodes
[7]	JSO-based Enhanced Energy Efficient LEACH (JSO-LEACH) Protocol	Average energy consumption 24.6686 J, average packet delivery ratio 66.5538%	Improved energy efficiency in IoT perception layer	Bio-inspired algorithm effectively addresses optimization challenges
[8]	State-of-the-art review on renewable energy harvesting in precision agriculture	N/A	N/A	Highlights potential applications and benefits of renewable energy in agriculture
[9]	Intelligent Reflecting Surfaces (IRS) for energy harvesting	Optimization methods improve energy harvesting potential	Efficient in enhancing wireless connectivity and signal strength	Addresses optimization challenges for future wireless networks
[10]	Hybrid Cuckoo Search Elephant Herding Optimization (HCSEHO)	Improved energy efficiency in CRSN routing	Efficient path selection and energy harvesting	Ensures reliable medical data transmission and extends network lifespan

[11]	Floor tile excited by human footsteps	Maximum power of 246 mW per tile	Effective in converting kinetic energy from footsteps	Practical and low-cost approach for energy harvesting from human motion
[12]	Fuzzy clustering and particle optimization for WSIoT	9.57% improvement in throughput, 8.47% reduction in energy consumption	Efficient in reducing energy consumption in IoT networks	Effective in addressing energy consumption and battery replacement challenges
[13]	IoT-based energy-efficient routing protocol for smart agriculture	N/A	N/A	Enhances productivity and energy efficiency in agriculture through IoT
[14]	IoT Heterogeneous Energy Harvesting (IHEH) technique	Overall efficiency of 90% per day	Highly efficient in managing various energy sources	Increases power yield and battery lifetime in smart home appliances
[15]	Energy-aware task scheduler for batteryless IoT devices	Continuous operation, executes more tasks with 10 mF capacitor at 40 μA	High efficiency in adapting to environmental changes	Avoids power failures, maintains forward progress in task execution
[16]	Feasibility evaluation approach for batteryless IoT devices	Effective in worst-case periods with peak energy consumption	Efficient in modeling high energy consumption periods	Simplifies characterization of wireless technology energy consumption
[17]	Runtime energy-allocation framework with rollout algorithm	Up to 35% higher utility, 1000× smaller energy overhead	Efficient in optimizing energy allocation	Effective in managing energy constraints, enhances utility
[18]	SWIPT with Optimal Transmit Power and PS Ratio (OTPR)	Near-optimal performance with shortest training time	Highly efficient in maximizing energy efficiency	Effective in minimizing co-channel interference and optimizing resource allocation
[19]	Energy-efficient	Improved network	Efficient in	Enhances network

	routing technique with EH-aware routing	longevity, efficient link selection	overcoming energy limitations	performance through efficient energy utilization
[20]	PPAASS for solar sensors	Higher average duty cycle, maximum of 15% unharvested solar energy	Highly efficient in real-time duty cycle adaptation	Ensures power availability, maximizes use of harvested energy
[21]	Soil-air Thermoelectric Generator (SoTEG)	Power density of 11.58 mW/m2, maximum power of 337 μW	Efficient in low-temperature differences	Impacted by weather conditions, potential for heat transfer efficiency improvement
[22]	Differential privacy and intelligent reflecting surface for 6G-enabled IoT	Effective privacy-preserving energy harvesting	Efficient in enhancing privacy and user satisfaction	Complexity in implementation and optimization
[23]	ViPSN-pluck (vibration-powered sensing node)	High energy reliability in transient-motion energy harvesting	Efficient in utilizing transient motion energy	Unique feature of high energy reliability under varying conditions
[24]	Sustainability in Dominating Set (SID) for solar energy harvesting	Improves residual energy by up to 25.6%, reduces message complexity by up to 88.5%	Efficient in energy management and reducing message complexity	Dependent on environmental conditions
[25]	Microwave power transfer with scalable rectenna design	High efficiency in dynamic power harvesting	Efficient in diverse power requirements and orientation insensitivity	Challenges with polarization and orientation mismatch
[26]	Triple-mode DC-DC converter for IoT edge nodes	Peak efficiency up to 88.7%	Highly efficient in varying energy sources and load conditions	Specific to CMOS process fabrication
[27]	Kinetic energy harvester model	Power output decreases with age	Efficient in large-scale data	Lower energy harvesting potential

	using UK Biobank data	and medical conditions	analysis	in older and diabetic participants
[28]	Deep Reinforcement Learning (REP-DRL) for energy sustainability	Adapts to varying conditions, conserves power in low battery and EH scenarios	Efficient in optimizing service offloading	Dependent on accurate RE predictions
[29]	Opportunistic Backscatter communication Medium access control (OBM) protocol	Improves network throughput and energy efficiency	Efficient in managing collisions and interference	Potential complexity in contention and communication techniques
[30]	Energy harvesting modulation (EHM) scheme for IIoT	Effective control reliability and energy harvesting	Efficient in integrated control state and energy transfer	Requires precise time slot selection
[31]	Dual-purpose radial-array rectenna	Average orientation estimation error of 1.0822°	Efficient in capturing RF energy and orientation sensing	Potential complexity in calibration and MMSE method
[32]	Miniaturized RF energy harvester with dual-polarized antennas	Conversion efficiency up to 71.4%	Highly efficient in various incident angles	Dependent on specific ISM frequency band
[33]	Imitation Learning (IL)-based energy management algorithm	Average allocation within 2.5 J of Oracle, energy consumption overhead of 154 μJ	Efficient in energy allocation and low overhead	Complexity in training and implementation
[34]	On-silicon inductor coil with integrated buck DC-DC converter	Efficiency up to 69.1% at 30 MHz	Efficient in low-power IoT scenarios	Limited to specific applications
[35]	Monte-Carlo ray-tracing simulation for OPV	Effective for indoor energy harvesting	Efficient in diffuse links for optical system	Complexity in numerical approaches

			performance	
[36]	Overview of RF energy harvesting and WPT technologies	Discusses flexible rectennas and SWIPT	Efficient in historical and recent technological advances	General overview without specific experimental validation
[37]	Lyapunov-chain offloading algorithm for UAV-based edge computing	Maintains strong energy stability, minimizes execution delay	Efficient in energy stability and computational offloading	Complexity in Lyapunov function construction
[38]	Quad-band energy harvester (QBEH) with E-CRLH TLs	Overall efficiency of 55%-70%	Efficient in broad input power range	Complexity in design and theoretical analysis
[39]	Active and passive integrated Reconfigurable Intelligent Surfaces (RIS)	Optimizes signal reflection and transmission	Efficient in managing signal throughput and exchanges	Complexity in optimization mechanism
[40]	Vibration-powered LoRaWAN-based sensor node	Ensures continuous operation with effective energy harvesting	Efficient for hard-to-reach positions	Dependent on specific vibration sources

Table 4. Comparative Results of Different Methods

Above is presented a detailed analysis of the comparison of different energy harvesting techniques applied in IoT. Each technique will be evaluated based on numerical results, efficiency evaluation, and observation related to energy harvesting. The findings show the strengths and limits of each approach so useful for researchers and practitioners in this field. Kept in view, further research will work towards the identified shortcomings and seek betterment for better efficiency and usability of the energy harvesting techniques in IoT networks.

5. Conclusion & Future Scopes

It evidences diversity and specificity in techniques used for energy efficiency optimization and therefore the extension of operational life for IoT devices, due to such detailed surveying of different energy harvesting models for IoT deployments. The explored innovative methods are residual time-based energy harvesting schemes, clustering-based algorithms, advanced power management units, bio-inspired, and hybrid optimization algorithms. These contribution methods underline some important improvements in the domain, responding to various challenges like energy efficiency, network stability, and sustainability of operations. In this regard, out of the models reviewed, the

clustering-based BAT algorithm and Improved Smart Energy-Based Routing Protocol bring out very high potential for improvement in network performance and lifetime through their optimized clustering and routing strategies. In particular, these models are very effective in scenarios that require high network stability and reduced operational cost, therefore suitable for smart agriculture and environmental monitoring applications. The residual time-based energy harvesting scheme [1], owing to its novelty in using idle slots for RF charging, is quite efficient for application on urban IoT networks where maximizing transmission rates and minimizing downtime are critical. The ViPSN-pluck model [23] and human footstep-based energy harvesting [11] are pretty pragmatic solutions, which can be scaled up and used with wearable and motion-based IoT devices. These models are very efficient in harvesting kinetic energy and thus provide a reliable power source for devices to be used in public places and health monitoring applications. First, this is further illustrated by the integration of TSS and REP-DRL, which then allows advanced techniques to include some of the best traditional energy harvesting with modern computational approaches for advanced energy management and resource allocation.
Such models should be fine-tuned in future research to reduce limitations and adapt to the evolving nature of IoT applications. Finally, this review emphasizes applications-specific energy harvesting solutions for a wide range of IoT applications. Algorithms based on clustering, like BAT, ISERP, and ViPSN-pluck, show great improvements in energy efficiency, network lifetime, and real-world deployment. Such adaptable methods, combined with robust performance metrics, allow for a real chance of future improvements toward sustainable IoT technology. In this respect, the continuous evolution of such approaches and further integration of new innovations can enable the field to achieve a higher order of energy autonomy and operational reliability and, therefore, help foster long-term and large-scale IoT deployments.

6. References

[1] Lin, YJ., Tzeng, SS. Residual Time Based Energy Harvesting for Framed Slotted ALOHA Based Wireless Powered IoT Networks. *Wireless Pers Commun* **136**, 347–363 (2024). https://doi.org/10.1007/s11277-024-11268-z

[2] Sahoo, B.M., Sabyasachi, A.S. A Metaheuristic Algorithm Based Clustering Protocol for Energy Harvesting in IoT-Enabled WSN. *Wireless Pers Commun* **136**, 385–410 (2024). https://doi.org/10.1007/s11277-024-11270-5

[3] Oukas, N., Boulif, M. & Arab, K. A novel fluid-based modeling approach using extended Hybrid Petri nets for power consumption monitoring in wireless autonomous IoT devices, with energy harvesting capability and triple sleeping strategy. *Wireless Netw* **30**, 1869–1892 (2024). https://doi.org/10.1007/s11276-023-03629-6

[4] Sheikh, A.M., Joshi, S. Improved smart energy-based routing approach for IoT networks in wireless sensor nodes. *J. Eng. Appl. Sci.* **71**, 103 (2024). https://doi.org/10.1186/s44147-024-00435-5

[5] Baek, D., Lee, H.G. On-Chip Energy Harvesting System with Storage-Less MPPT for IoTs. *J. Electr. Eng. Technol.* **18**, 1873–1882 (2023). https://doi.org/10.1007/s42835-023-01436-9

[6] Wu, Z., Cao, Z., Teng, J. *et al.* Electrostatic generator enhancements for powering IoT nodes via efficient energy management. *Microsyst Nanoeng* **10**, 30 (2024). https://doi.org/10.1038/s41378-024-00660-1

[7] Hasan, A., Patle, V.K. JSO-based enhanced energy efficient LEACH protocol for IoT-perception layer. *Int. j. inf. tecnol.* **16**, 979–991 (2024). https://doi.org/10.1007/s41870-023-01613-z

[8] Khernane, S., Bouam, S. & Arar, C. Renewable Energy Harvesting for Wireless Sensor Networks in Precision Agriculture. *Int J Netw Distrib Comput* **12**, 8–16 (2024). https://doi.org/10.1007/s44227-023-00017-6

[9] Vishwakarma, P., Bhattacharjee, D., Dhar, S. *et al.* A Comprehensive Review on Beamforming Optimization Techniques for IRS assisted Energy Harvesting. *Arch Computat Methods Eng* (2024). https://doi.org/10.1007/s11831-024-10118-2

[10] Kumar, B.N., Singh, J.S.P. Development of multi-objective cognitive radio network with energy harvesting for medical data transmission. *Peer-to-Peer Netw. Appl.* **16**, 2131–2152 (2023). https://doi.org/10.1007/s12083-023-01519-4

[11] Selim, K.K., Yehia, H.M. & Saleeb, D.A. Energy Harvesting Floor Tile Using Piezoelectric Patches for Low-Power Applications. *J. Vib. Eng. Technol.* (2024). https://doi.org/10.1007/s42417-024-01379-z

[12] Javadpour, A., Sangaiah, A.K., Zaviyeh, H. *et al.* Enhancing Energy Efficiency in IoT Networks Through Fuzzy Clustering and Optimization. *Mobile Netw Appl* (2023). https://doi.org/10.1007/s11036-023-02273-w

[13] kumar, C.S., Anand, R.V. A Review of Energy-Efficient Secured Routing Algorithm for IoT-Enabled Smart Agricultural Systems. *J. Biosyst. Eng.* **48**, 339–354 (2023). https://doi.org/10.1007/s42853-023-00192-y

[14] J. Bharathi Madavarapu, H. Islam, A. Appathurai, G. Ali Safdar, N. Muthukumaran and J. Gnanamalar, "Heterogeneous Energy Harvesting Techniques for Smart Home IoT Acceleration," in IEEE Access, vol. 12, pp. 73667-73675, 2024, doi: 10.1109/ACCESS.2024.3397664.
keywords: {Sensors;Internet of Things;Batteries;Smart homes;Energy harvesting;Home appliances;Wireless sensor networks;Home automation;Energy consumption;IoT;smart home;energy harvesting;household power;domestic energy},

[15] A. Sabovic, A. K. Sultania, C. Delgado, L. D. Roeck and J. Famaey, "An Energy-Aware Task Scheduler for Energy-Harvesting Batteryless IoT Devices," in IEEE Internet of Things Journal, vol. 9, no. 22, pp. 23097-23114, 15 Nov.15, 2022, doi: 10.1109/JIOT.2022.3185321.
keywords: {Task analysis;Internet of Things;Capacitors;Performance evaluation;Behavioral sciences;Energy harvesting;Batteries;Batteryless Internet of Things (IoT);Bluetooth low energy (BLE);energy harvesting;energy-aware task scheduler;intermittent computing;sustainable IoT},

[16] D. Van Leemput, A. Sabovic, K. Hammoud, J. Famaey, S. Pollin and E. De Poorter, "Energy Harvesting for Wireless IoT Use Cases: A Generic Feasibility Model and Tradeoff Study," in IEEE Internet of Things Journal, vol. 10, no. 17, pp. 15025-15043, 1 Sept.1, 2023, doi: 10.1109/JIOT.2023.3263543.
keywords: {Wireless communication;Internet of Things;Wireless sensor networks;Energy harvesting;Energy consumption;Capacitors;Supercapacitors;6TiSCH;Bluetooth low energy (BLE);energy harvesting;feasibility study;Internet of Things (IoT);long range wide area network (LoRaWAN)},

[17] Y. Tuncel, G. Bhat, J. Park and U. Y. Ogras, "ECO: Enabling Energy-Neutral IoT Devices Through Runtime Allocation of Harvested Energy," in IEEE Internet of Things Journal, vol. 9, no. 7, pp. 4833-4848, 1 April1, 2022, doi: 10.1109/JIOT.2021.3106283.
keywords: {Batteries;Energy harvesting;Runtime;Resource management;Optimization;Internet of Things;Wearable computers;Battery management;energy efficiency;energy harvesting (EH);Internet of Things (IoT);optimization;resource allocation},

[18] S. Alzahrani, A. Salh, L. Audah, M. A. Alhartomi, A. Alotaibi and R. Alsulami, "Empowering Energy-Sustainable IoT Devices With Harvest Energy-Optimized Deep Neural Networks," in IEEE Access, vol. 12, pp. 70600-70614, 2024, doi: 10.1109/ACCESS.2024.3399563.
keywords: {Internet of Things;Training;Artificial neural networks;Wireless communication;Quality of service;Interference;Batteries;Energy efficiency;Artificial neural networks;Energy harvesting;Low-power electronics;Internet of Things;energy efficiency;power splitting;deep neural network;energy harvesting},

[19] H. Zeb, A. Ghani, M. Gohar, A. Alzahrani, M. Bilal and D. Kwak, "Location Centric Energy Harvesting Aware Routing Protocol for IoT in Smart Cities," in IEEE Access, vol. 11, pp. 102352-102365, 2023, doi: 10.1109/ACCESS.2023.3317268.
keywords: {Routing;Energy harvesting;Internet of Things;Routing protocols;Wireless sensor networks;Energy efficiency;Costs;The Internet of Things;smart cities;energy harvesting;routing protocol;energy efficiency},

[20] A. Cinco-Solis, J. J. Camacho-Escoto, L. Orozco-Barbosa and J. Gomez, "PPAASS: Practical Power-Aware Duty Cycle Algorithm for Solar Energy Harvesting Sensors," in IEEE Access, vol. 10, pp. 117855-117870, 2022, doi: 10.1109/ACCESS.2022.3220695.
keywords: {Batteries;Prediction algorithms;Performance evaluation;Solar energy;Photovoltaic cells;Energy harvesting;Solar panels;Energy management ;Green products;Energy harvesting;energy management;green IoT;Internet of Things;solar energy},

[21] P. P. Puluckul and M. Weyn, "Harvesting Energy From Soil-Air Temperature Differences for Batteryless IoT Devices: A Case Study," in IEEE Access, vol. 12, pp. 85306-85323, 2024, doi: 10.1109/ACCESS.2024.3414652.
keywords: {Soil measurement;Thermal energy;Heat sinks;Internet of Things;Heating systems;Heat transfer;Atmospheric modeling;Energy harvesting;Sustainable development;Thermoelectric devices;Energy harvesting;Internet of Batteryless Things;soil thermal energy;sustainability;thermal energy;thermoelectric generators},

[22] Q. Pan, J. Wu, X. Zheng, W. Yang and J. Li, "Differential Privacy and IRS Empowered Intelligent Energy Harvesting for 6G Internet of Things," in IEEE Internet of Things Journal, vol. 9, no. 22, pp. 22109-22122, 15 Nov.15, 2022, doi: 10.1109/JIOT.2021.3104833.
keywords: {Privacy;6G mobile communication;Energy harvesting;Energy exchange;Resource management;Differential privacy;Wireless communication;Differential privacy (DP);energy harvesting (EH);intelligent reflecting surface (IRS);Internet of Things (IoT);privacy preservation},

[23] X. Li, H. Tang, G. Hu, B. Zhao and J. Liang, "ViPSN-Pluck: A Transient-Motion-Powered Motion Detector," in IEEE Internet of Things Journal, vol. 9, no. 5, pp. 3372-3382, 1 March1, 2022, doi: 10.1109/JIOT.2021.3098238.
keywords: {Sensors;Internet of Things;Energy harvesting;Motion detection;Radio frequency;Reliability;Detectors;Battery-free Internet of Things (IoT);energy harvesting;motion detector;plucking;ubiquitous sensing},

[24] C. R. Chowdhury, C. Mandal and S. Misra, "Sustainable Maintenance of Connected Dominating Set by Solar Energy Harvesting for IoT Networks," in IEEE Transactions on Green Communications and Networking, vol. 6, no. 4, pp. 2115-2127, Dec. 2022, doi: 10.1109/TGCN.2022.3175035.
keywords: {Maintenance engineering;Green products;Approximation algorithms;Solar panels;Solar energy;Hysteresis;Energy harvesting;Connected dominating set;node disjoint maximum weighted independent set;maximum connected Steiner tree;approximation algorithm;solar energy harvesting;sustainable},

[25] M. Kumar, S. Kumar, S. Jain and A. Sharma, "A Plug-in Type Integrated Rectenna Cell for Scalable RF Battery Using Wireless Energy Harvesting System," in IEEE Microwave and Wireless Technology Letters, vol. 33, no. 1, pp. 98-101, Jan. 2023, doi: 10.1109/LMWC.2022.3202711.
keywords: {Rectennas;Radio frequency;Batteries;Energy harvesting;Antennas;Wireless communication;Manganese;Internet of things (IoT);microwave power transfer;polarization;rectenna;scalability;wireless energy harvesting (WEH)},

[26] J. Yang, B. Li, K. N. Leung, Z. Chen and Y. Zheng, "A Triple-Mode DC–DC Converter With Wide Input and Load Ranges for Energy Harvesting in IoT Edge Nodes," in IEEE Transactions

on Circuits and Systems II: Express Briefs, vol. 69, no. 12, pp. 4694-4698, Dec. 2022, doi: 10.1109/TCSII.2022.3196029.
keywords: {Switches;Batteries;Control systems;Inductors;Voltage control;Energy harvesting;Numerical analysis;Automatic buck-boost;dc-dc converters;energy harvesting;maximum-power-point tracking (MPPT)},

[27] C. Beach and A. J. Casson, "Estimation of Kinetic Energy Harvesting Potential for Self-Powered Wearable IoT Devices With 67 000 Participants From the UK Biobank," in IEEE Internet of Things Journal, vol. 11, no. 1, pp. 490-501, 1 Jan.1, 2024, doi: 10.1109/JIOT.2023.3288212.
keywords: {Energy harvesting;Internet of Things;Kinetic energy;Wearable computers;Accelerometers;Data models;Biomedical monitoring;Big data applications;energy harvesting},

[28] M. Alhartomi, A. Salh, L. Audah, S. Alzahrani and A. Alzahmi, "Enhancing Sustainable Edge Computing Offloading via Renewable Prediction for Energy Harvesting," in IEEE Access, vol. 12, pp. 74011-74023, 2024, doi: 10.1109/ACCESS.2024.3404222.
keywords: {Internet of Things;Batteries;Task analysis;Energy consumption;Sustainable development;Renewable energy sources;Optimization;Edge computing;Energy harvesting;Edge computing;energy harvesting;IoT;RE;DRL},

[29] A. Iqbal and T. -J. Lee, "Opportunistic Backscatter Communication Protocol Underlying Energy Harvesting IoT Networks," in IEEE Access, vol. 11, pp. 89568-89580, 2023, doi: 10.1109/ACCESS.2023.3306777.
keywords: {Backscatter;Wireless sensor networks;Wireless communication;Energy harvesting;Protocols;Internet of Things;Radio frequency;Internet of Things (IoT);wireless energy harvesting;medium access control (MAC);backscatter communications},

[30] Y. Zhao, Y. Wu, J. Hu, K. Yang and B. Clerckx, "Energy Harvesting Modulation for Integrated Control State and Energy Transfer in Industrial IoT," in IEEE Wireless Communications Letters, vol. 12, no. 2, pp. 292-296, Feb. 2023, doi: 10.1109/LWC.2022.3224300.
keywords: {Receivers;Industrial Internet of Things;Energy harvesting;Wireless communication;Radio frequency;Energy exchange;Wireless sensor networks;Energy harvesting modulation(EHM);integrated control state and energy transfer (ICSET);wireless energy transfer (WET);wireless control state transfer (WCST);industrial IoT (IIoT)},

[31] M. Kumar, S. Kumar and A. Sharma, "Dual-Purpose Planar Radial-Array of Rectenna Sensors for Orientation Estimation and RF-Energy Harvesting at IoT Nodes," in IEEE Microwave and Wireless Components Letters, vol. 32, no. 3, pp. 245-248, March 2022, doi: 10.1109/LMWC.2022.3145196.
keywords: {Rectennas;Sensors;Wireless sensor networks;Radio frequency;Antennas;Antenna arrays;Wireless communication;Antenna array;Internet of Things (IoT);localization;rectenna;RF energy harvesting (EH);wireless sensor nodes},

[32] J. -S. Park, Y. -S. Choi and W. -S. Lee, "Design of Miniaturized Incident Angle-Insensitive 2.45 GHz RF-Based Energy Harvesting System for IoT Applications," in IEEE Transactions on Antennas and Propagation, vol. 70, no. 5, pp. 3781-3788, May 2022, doi: 10.1109/TAP.2021.3137481.
keywords: {Radio frequency;Energy harvesting;Dipole antennas;Antennas;Antenna measurements;Internet of Things;RF signals;Angle insensitive;dual-polarized;miniaturized;radio frequency (RF)-based energy harvesting system;rectifier circuit},

[33] N. Yamin and G. Bhat, "Near-Optimal Energy Management for Energy Harvesting IoT Devices Using Imitation Learning," in IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems, vol. 41, no. 11, pp. 4551-4562, Nov. 2022, doi: 10.1109/TCAD.2022.3198909.

keywords: {Internet of Things;Resource management;Batteries;Optimization;Runtime;Quality of service;Heuristic algorithms;Energy harvesting (EH);energy management (EM);energy neutral operation (ENO);imitation learning (IL);Internet of Things (IoT) devices;wearable health monitoring systems},

[34] N. N. Xu, Y. An, H. Yu and J. Yang, "A Study of the Fully On-Chip Inductor Coils for 30 MHz Power Regulation Applications in Energy Harvesting, Sensor Networks, and IoT Scenarios," in IEEE Sensors Letters, vol. 7, no. 4, pp. 1-4, April 2023, Art no. 5501404, doi: 10.1109/LSENS.2023.3262736.
keywords: {Inductors;System-on-chip;Inductance;Coils;Metals;Internet of Things;Sensors;Sensor systems;on-chip inductor;energy harvesting;internet of things (IoT);power regulation;sensor applications},

[35] D. R. D. Santos et al., "Toward Indoor Simulations of OPV Cells for Visible Light Communication and Energy Harvesting," in IEEE Access, vol. 12, pp. 41027-41041, 2024, doi: 10.1109/ACCESS.2024.3378056.
keywords: {Optical receivers;Optical reflection;Optical transmitters;Optical saturation;Lighting;Optical amplifiers;Energy harvesting;Channel models;Energy harvesting;Channel estimation;Photovoltaic systems;Visible light communication;Channel modeling;experimental demonstration;indoor energy harvesting;optical channel simulation;organic photovoltaics;visible light communication},

[36] K. Niotaki et al., "RF Energy Harvesting and Wireless Power Transfer for Energy Autonomous Wireless Devices and RFIDs," in IEEE Journal of Microwaves, vol. 3, no. 2, pp. 763-782, April 2023, doi: 10.1109/JMW.2023.3255581.
keywords: {Radio frequency;Wireless communication;Performance evaluation;5G mobile communication;Rectennas;Radio transmitters;Millimeter wave technology;Backscatter;wireless communications;electromagnetic harvesting;RF energy harvesting;IoT;wireless power transfer;energy harvesting;rectenna;antenna array;millimeter-wave;flexible rectennas;simultaneous wireless information and power transfer;MTT 70th Anniversary Special Issue},

[37] K. Zeng, X. Li and T. Shen, "Energy-Stabilized Computing Offloading Algorithm for UAVs With Energy Harvesting," in IEEE Internet of Things Journal, vol. 11, no. 4, pp. 6020-6031, 15 Feb.15, 2024, doi: 10.1109/JIOT.2023.3309136.
keywords: {Internet of Things;Autonomous aerial vehicles;Energy harvesting;Computational modeling;Task analysis;Servers;Energy consumption;Computing offloading;edge computing;energy harvesting;Lyapunov;unmanned aerial vehicle based (UAV)},

[38] R. Keshavarz and N. Shariati, "Highly Sensitive and Compact Quad-Band Ambient RF Energy Harvester," in IEEE Transactions on Industrial Electronics, vol. 69, no. 4, pp. 3609-3621, April 2022, doi: 10.1109/TIE.2021.3075888.
keywords: {Rectifiers;Radio frequency;Energy harvesting;Mathematical model;Sensors;Impedance;Wireless sensor networks;Ambient energy harvesting;electromagnetic (EM) energy;high efficiency;Internet of Things (IoTs);quad-band rectifier;rectenna (rectifying antenna);wide input power range},

[39] S. Ahmed, A. E. Kamal, M. Y. Selim, S. R. Sabuj and M. Hamamura, "Revolutionizing Batteryless IoT Systems to Enhance Nonlinear Energy Harvesting Using RIS Active and Passive Elements," in IEEE Open Journal of the Communications Society, vol. 5, pp. 3021-3037, 2024, doi: 10.1109/OJCOMS.2024.3393480.
keywords: {Reconfigurable intelligent surfaces;Internet of Things;Energy harvesting;Wireless communication;Wireless sensor networks;Wireless networks;Device-to-device communication;Batteryless IoT sensor;D2D communications;nonlinear energy harvesting model;RIS active and passive elements},

[40] Rigo F, Migliorini M, Pozzebon A. Piezoelectric Sensors as Energy Harvesters for Ultra Low-Power IoT Applications. *Sensors*. 2024; 24(8):2587. https://doi.org/10.3390/s24082587