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Review

Review of Next-Generation Wireless Devices with Self-Energy Harvesting for Sustainability Improvement

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Abstract: Wireless methodologies are the focal point of electronic devices, including telephones, computers, sensors, mobile phones, laptops, and wearables. However, wireless technology is not yet utilized extensively in underwater and deep-space communications applications, and it is also not applied in certain critical medical, military, and industrial applications due to its limited battery life. Self-energy-harvesting techniques overcome this issue by converting ambient energy from the surroundings into usable power for electronic devices; devices that use such techniques are next-generation wireless devices that can operate without relying on external power sources. This methodology improves the sustainability of the wireless device and ensures its prolonged operation. This article gives an in-depth analysis of the recent techniques that are implemented to design an efficient energy-harvesting wireless device. It also summarizes the most preferred energy sources and generator systems in the present trends. This review and its summary explore the common scope of researchers in narrowing their focus in designing new self-energy-harvesting wireless devices.

Keywords: eco-friendly devices; self-energy harvesting; sustainable devices; wireless power transfer; next-generation networks

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1. Introduction

Electronic gadgets and tools that are used to communicate device-to-device and device-to-human through wireless communication are termed wireless devices. Radio waves and infrared signals are some of the widely preferred wireless communication methods due to their reliability and flexible installation. Wireless communication technologies are categorized based on their signal strength and communication distance. Smartphones, laptops, smartwatches, Wi-Fi routers, Bluetooth speakers, and wireless headphones are some of the familiar wireless devices used in day-to-day life. The wireless connectivity in such devices is established through internal or external adapters and receivers. Therefore, wireless devices have the ability to move around anywhere in the network area; furthermore, the constraints of physical cables and wires are eliminated. In recent years, wireless communication devices have been incorporated into various sectors for improving their mobility and productivity [1–5]. Figure 1 shows sectors that have been widely updated with wireless communication in recent days.

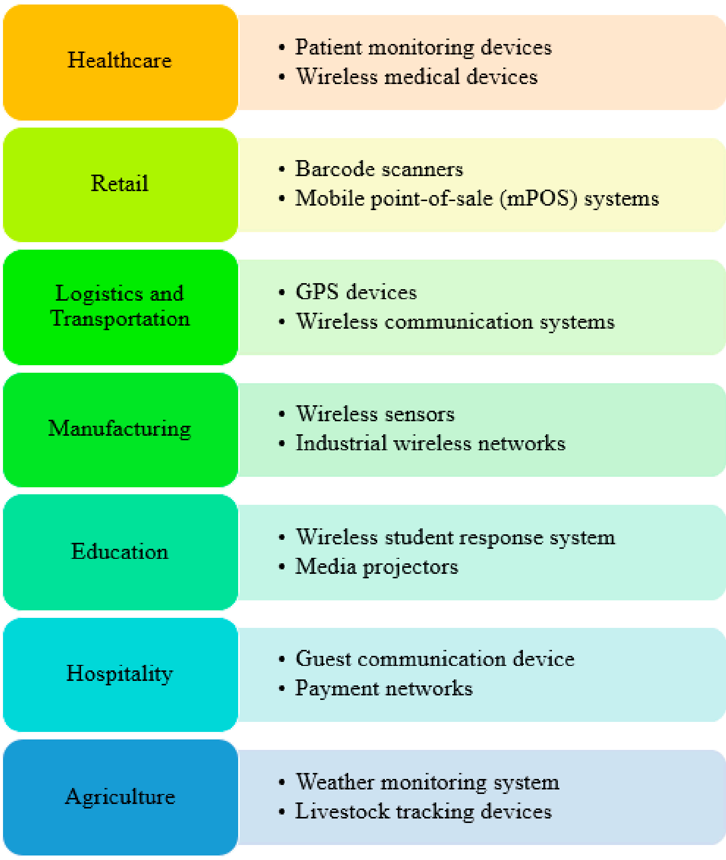

Figure 1. Wireless devices in various sectors.

1.1. Healthcare

Wearable sensors and remote monitoring devices are implemented in recent days to provide a continuous patient-monitoring environment. In some applications, such devices are programmed to create an alert signal upon the critical condition of a patient. The measured readings and signals are transferred to healthcare providers for treatment planning. Medical devices such as pacemakers, insulin pumps, and implantable devices are also equipped with wireless connectivity for improving healthcare system reliability.

1.2. Retail

Handheld barcode scanners have been developed with wireless connectivity for assisting retail workers in providing remote inventory management and price-checking processes. Mobile-POS (point of sale) is the system that is used in retail applications to make contactless payments. Hence, it reduces the purchasing time and improves the flexibility on the payment process.

1.3. Logistic and Transportation

Wireless devices that can access the Global Positioning System (GPS) are utilized in logistic applications for tracking the location of shipments and vehicles in real-time. Similarly, two-way radios and mobile devices are employed in transportation systems to make efficient and timely communication between transport personnel and logistic coordinators.

1.4. Manufacturing or Industrial Sector

Sensors that are equipped with wireless systems are efficient in transmitting the performance and environmental state of the connected equipment. At the same time, such systems are effective in planning process optimization and predictive maintenance. The industrial wireless networks are utilized to provide communication signals between the connected devices, machines, and control units for making an efficient automation system.

1.5. Education

Projectors are connected with computers/laptops/mobile phones for providing wireless media access to the user. This allows the student to view digital content in a perfect way without any peripheral connection. Handheld devices are utilized in certain cases, such as student response systems for marking attendance; other interaction activities such as quizzes are provided thorough additional mobile apps.

1.6. Hospitality

Smartphones and special devices that are equipped with special apps allow customized communication between a guest and the service provider for various requests. To increase customer convenience, direct and indirect payments are made with a wireless point-of-service device.

1.7. Agriculture

The wireless weather monitoring system is one of the most widely used applications of wireless devices; in this device, the sensors are connected to gather plenty of data from the environment to assist the farmer in planning irrigation, crop prediction, and other related activities. In certain applications, the sensors are utilized to monitor the health status of crops from a remote location. This enables farmers to notice several plant diseases at the beginning stage.

The performance of any wireless device may degrade with respect to the functionality factors presented in Table 1.

Table 1. Performance-degrading factors of wireless devices.

Functionality Factors	Description
Signal strength	Distance between the access points, and interference from other devices and obstacles are some of the issues that affect the signal strength of a wireless device.
Interference	Signals from devices that use the same frequency range, such as microwave ovens, cordless mics, and Bluetooth headphones, may interfere with each other and degrade signals' performance in terms of response speed and disconnection.
Frequency band	2.4 GHz and 5 GHz are the most preferred frequency bands for wireless device operation. Comparatively, 2.4 GHz devices receive interference more easily than 5 GHz devices, but 5 GHz devices can be active only for shorter distances of operation.
Channel congestion	Congestion happens in a crowded environment where multiple wireless devices are active. This degrades wireless device performance in terms of response speed and irregular operation.
Environmental factors	Weather conditions, building materials, geographical terrain, and reflective surfaces are some of the environmental factors that impact the signal strength and coverage of a wireless system.
Power source	Wireless devices such as smartphones and laptops are highly dependent upon the energy availability in the device's battery source. Battery level also has a small impact over the signal strength of a wireless connection.

2. Significance of Energy Harvesting for Wireless Devices

2.1. Sustainability

Most wireless devices such as smartphones and wearables work based on the power availability in their connected battery source. However, the energy stored in the battery may drain in an irregular manner based on the operational speed and performance of the connected device. Therefore, it is always expected that users will monitor the energy level of a battery to provide uninterrupted service. Recharging is one of the primary methods that allows the battery to restore its energy. In some cases, the battery is replaced with a new or recharged battery for the device's continuous operation. Self-energy harvesting is incorporated in very rare cases in recent days for increasing the sustainability of the battery-connected device [6].

2.2. Extended Battery Life

Ambient sources such as solar and kinetic energy are widely preferred in wireless devices for restoring the energy in battery modules. This minimizes the downtime and enhances the operation without a frequent recharge or replacement of a battery. Self-energy harvesting methodologies can also increase the operational time of wireless devices in some critical locations [7].

2.3. Mobility

Wireless devices are expected to be independent and more mobile than any other devices. Self-energy harvesting allows wireless devices to meet such expectations, and it allows devices to be operated in off-grid and remote locations for many hours without an external power source requirement. This allows wireless devices to act as outdoor sensors, which can be integrated with IoT technology [8].

2.4. Scalability and Flexibility

Wireless devices with self-energy harvesting can be deployed at any critical locations that cannot be facilitated with a power infrastructure. Therefore, the scalability of such devices can be improved to a certain extent, and the flexibility of such wireless devices allows the system to be incorporated with any other distributed applications [9].

2.5. Reliability and Redundancy

Self-energy-harvesting wireless devices are highly reliable, as they store energy for their own operation. Wire-connected devices operate based on the energy available in their connected terminal; this type of device really suffers during power-outage periods. In addition, the power fluctuation is comparatively minimal in battery-connected devices over the traditional AC circuit. Therefore, it enhances the life of wireless devices. Similarly, the redundancy of wireless devices is also very high, as they do not require any frequent or periodic maintenance [10].

2.6. Environmental Impact

Wireless devices are highly operated from renewable energy sources, and that reduces their carbon footprint. Therefore, wireless devices that are incorporated with a self-sustainable power source are widely acceptable in various sectors and nations [11].

2.7. Cost Efficiency

The operational cost of a wireless device is very low when it is implemented with a self-sustainable energy source as it does not require any replacement or recharging infrastructure [12]. Table 2 indicates the merits of self-energy-harvesting devices.

Table 2. Merits of self-energy-harvesting wireless devices.

Merits	Description
Hassle-free deployment	Absence of wire allows these devices to be plug-and-play.
Non-stop operation	Guarantees continuous operation, as the battery does not need to be replaced.
Compactness	Suitable for ultra-low-power industrial circuits.
Feasibility	Can be employed in places which are unsafe and hard to reach for maintenance.
Power backup	Harvested energy can be stored in a battery source if required.

3. Limitations of Self-Harvesting Wireless Devices

Self-harvesting wireless devices are designed to address the energy source constraint in regular wireless devices [13–15]. However, self-harvesting wireless devices also have certain limitations, as specified in Figure 2.

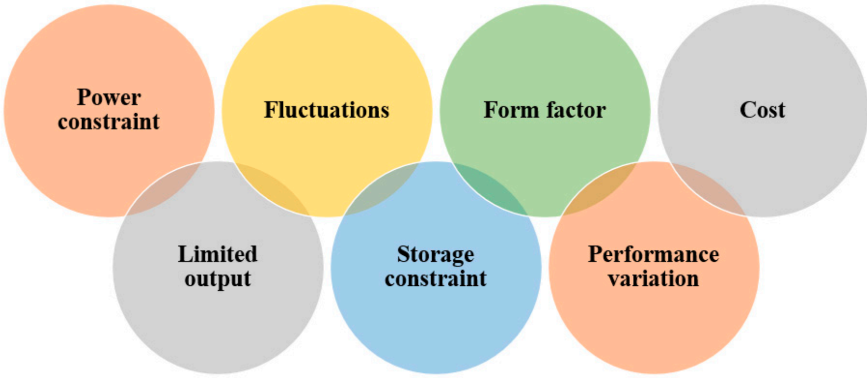

Figure 2. Performance-degrading factors of self-harvesting wireless devices.

3.1. Power Generation Constraints

Self-harvesting systems for wireless devices are highly reliant on environmental considerations. The amount of energy generated is limited when there is reduced solar, thermal, or kinetic energy in the surroundings. For example, solar-powered wireless devices may struggle with respect to solar energy intensity and availability in their surroundings. The performance may degrade on shaded and low-light conditions.

3.2. Limited Power Output

The power generated by a self-harvesting methodology cannot be the same as that of battery-powered energy sources. The generated energy can be sufficient for some low-power operations and low-energy devices; similarly, it cannot be utilized for high-power or high-performance applications.

3.3. Intermittent Power

Self-energy devices are open to energy fluctuations based upon the available energy source. The changes in irregular environmental conditions may lead generators to harvest irregular power outcomes. This kind of intermittent supply may damage the critical circuits of a wireless device, and in some cases, it may lead to interruption and data loss.

3.4. Energy Storage Constraint

Even when wireless devices are equipped with a self-harvesting energy supply, they may require an additional battery source for storage purposes. The saved energy in the battery may be required for some future operation. Rechargeable batteries and capacitors are some of the most used storage methodologies. However, such methodologies are heavily affected by degradation over time and self-discharge. Therefore, the use of batteries can affect the overall efficiency and reliability of the system.

3.5. Device Design and Form Factor

The integration of self-harvesting methodology into a wireless system may increase its size and weight. Therefore, it can limit the device design and form factor on miniaturization, portability, and wearable operation.

3.6. Cost

The installation and manufacturing cost of self-energy wireless devices are comparatively higher than battery-powered devices. The cost of energy-harvesting components, energy storage systems, and power regulatory models makes such systems costlier.

3.7. Performance Variability

The performance of self-harvesting wireless devices may vary based on the technology used for energy generation, user behaviour, and environmental conditions. Location, exposure to the energy source, orientation, and movement patterns are also some of the functionality factors that affect the performance of wireless devices. In some cases, these factors cause the reliability and predictability of wireless devices to be questionable. However, certain power optimization algorithms and methodologies have been developed in recent years to address such issues. The following section explores the present trend in such optimization models.

4. Energy-Harvesting Methodologies for Wireless Devices

Wireless devices are structured with different methodologies for converting ambient energy into useful energy. Solar, kinetic, and thermal energy utilization are some of the widely implemented energy-harvesting methods in wireless devices. Figure 3 indicates the energy-harvesting methods that are used in various applications.

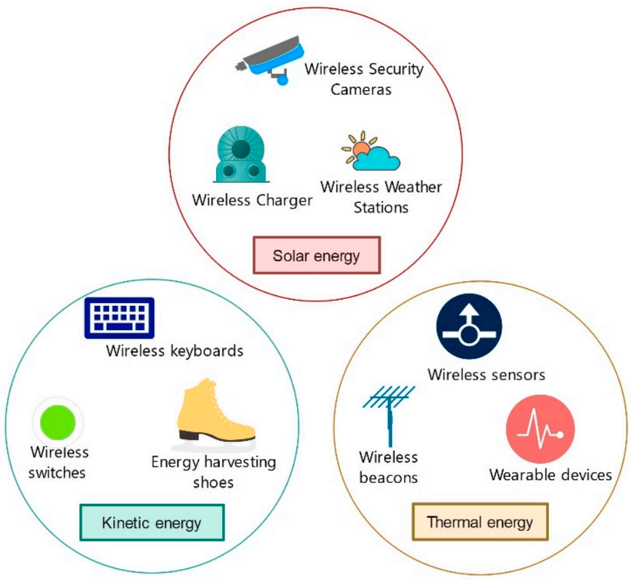

Figure 3. Applications of self-energy-harvesting techniques in wireless devices.

4.1. Solar Energy Harvesting

Solar energy harvesting is one of the most commonly used methods for energy harvesting; it utilizes photovoltaic cells to convert sunlight into electrical energy. The photovoltaic cell absorbs photons from sunlight to generate an electric current. Its use can be seen in devices from a small-size calculator to large-scale solar power plants.

4.2. Thermal Energy Harvesting

Thermal-energy-harvesting methods generate electricity through sensing units that observe temperature differences. Thermoelectric materials are utilized to observe heat gradients for generating electrical voltage. Therefore, these methodologies can be implemented in industrial applications where there is a huge temperature differential.

4.3. Kinetic Energy Harvesting

Kinetic energy harvesting can also be represented as a motion-based energy-harvesting method where the movement or motion of an object is used for generating electric power. This is a most common methodology used in wearable devices and self-powered sensor units. Electromagnetic induction and piezoelectric materials are used to convert mechanical motion into electric power.

4.4. Hybrid Energy-Harvesting Technology

Hybrid energy-harvesting methods are designed by integrating multiple energy-harvesting methods. This method is preferred for wireless devices due to its high reliability and better energy efficiency. Some of the important hybrid energy systems used for wireless devices are discussed below.

4.4.1. Solar-Energy-Based Hybrid Energy-Harvesting Methods

Arora et al., 2022 [16] developed a hybrid system based on a solar, thermal, and piezoelectric model for underwater WSN applications. A novel optimization method was also proposed in this work, and the theoretical calculation provides an energy outcome of 22.3 KJ per 24 h. Chen et al., 2022 [17] proposed a solar-panel- and wind-turbine-based hybrid energy system for mobile edge-computing systems where a dynamic offloading algorithm is utilized to regularize the generated power. Xiao et al., 2023 [18] made a hybrid model with solar PV and a thermoelectrical generator to convert the ambient light and heat energy in a room into useful power. The work uses a five-sided PV panel for this operation, and the generated power is used for IoT sensors for increasing its sustainability. Kim et al., 2022 [19] designed a hybrid system with a raindrop- and solar-energy-harvesting method. The work contains a triboelectric nanogenerator constructed with an inbuilt charge storage layer in the PV panel. The design was implemented in an invisible IoT security system and obtained a satisfactory outcome in terms of energy efficiency due to a better light-transmittance rate.

4.4.2. Thermal-Energy-Based Hybrid Energy-Harvesting Methods

Bakytbekov et al., 2022 [20] designed an RF- and thermal-based self-energy-harvesting dual-function triple-band antenna for IoT application. The experimental test indicates that this methodology provides an energy outcome of 13.6 µW with 250 mV. Kim et al., 2022 [21] framed a hybrid energy-harvesting model by integrating triboelectric and thermoelectric generators for wearable device applications. The work converts body motion and body heat into useful electric energy, and the experimental work took 240 s to store energy in a 3.3 mF capacitor of 3 V. Yang et al., 2022 [22] developed a hybrid energy-harvesting device that includes s triboelectric nanogenerator and thermoelectric generator. The work utilizes the inevitable heat produced from the Seebeck effect and that gives a betterment of 28 times over the traditional methods. Bakytbekov et al., 2023 [23] designed a multisource energy-harvesting system using an RF- and thermal-energy harvester. The experimental study gives a betterment of 10% over the traditional methods and produced 3680 µWh per day; further, it had the ability to transfer the data to the destination every 3.5 s.

4.4.3. Kinetic-Energy-Based Hybrid Energy-Harvesting Methods

Zhao et al., 2022 [24] structured a hybrid energy-harvesting model with piezoelectric and electromagnetic models for converting rotation and vibration energy into electric power. A triboelectric nanogenerator is utilized in this method for such energy conversion, and the work is implemented for wireless tire-pressure monitoring systems. Bai et al., 2023 [25] proposed a vibration- and rotation-energy-conversion model for wearable sensor electronics. The design is structured with electromagnetic and turboelectric generators and produces 300 mW from jogging and 800 mW from sprinting. The capability of the model can charge a wearable smartband rated with 400 mW power. Liu et al., 2023 [26] developed a marine-mammal-condition monitoring system with a triboelectric nanogenerator and micro-thermoelectric generator for making a self-powered device. The experimental work finds a betterment of 4.93% than the single energy source method of charging a battery. Cheng et al., 2023 [27] structured a hybrid energy-harvesting method that consists of piezoelectric, electromagnetic, and magnetostrictive generators. The experimental outcome gives a maximum output of 2.674 mW in Bluetooth wireless communication of humidity sensor data.

Hybrid energy systems are widely preferred in wireless devices for improving the reliability and sustainability of the connected systems. The self-hybrid energy systems are good for improving the battery life of the connected system by enhancing the energy-harvesting space to certain extent. Similarly, the hybrid model improves the system flexibility by adapting it for various applications. However, there are certain limitations in self-energy-harvesting systems, which are described in the following section.

5. Literature Review of Energy Optimization Models in Wireless Devices

Energy optimization is a methodology utilized to improve the power efficiency of energy harvesting by minimizing energy wastage. Usually, energy auditing will be implemented in every self-energy-harvesting system for analyzing its energy utilization pattern, and from that, a customized energy optimization algorithm will be developed. Table 3 represents some of the energy optimization methods utilized in wireless sensor networks and IoT applications.

Table 3. Literature review of energy optimization methods.

Methodology	Year	Energy Source	Generator Type	Application	Outcome
Multistage Dickson charge pump circuit [28]	2023	Electromagnetic wave	Multi-band RF antenna	IoT/WSN	78.3% of power conversion efficiency
Relay selection method [29]	2023	Electromagnetic wave	RF antenna	WBAN	7.8% of pocket reception rate improvement
Power control method [30]	2022	Electromagnetic wave	RF antenna	IoT sensor with NodeMCU	Reduced power requirement from 225 mW to 264 µW
Adaptive power transfer algorithm [31]	2022	Electromagnetic wave	RF antenna	IoT	49.5 mW outcome of wireless power transfer
Distributed resource management algorithm [32]	2021	Electromagnetic wave	RF antenna	B5G	Eight times reduced pocket loss compared to greedy algorithm
10-stage cross connected rectifier optimization [33]	2021	Electromagnetic wave	RF antenna	IoT	42.4% of peak end-to-end efficiency
Self-designed data and energy integrated network [34]	2021	Electromagnetic wave	RF antenna	IoT	Minimizes the sampling data to improve the sleeping time

Table 3. *Cont.*

Methodology	Year	Energy Source	Generator Type	Application	Outcome
Simultaneous wireless information and power transfer algorithm [35]	2021	Electromagnetic wave	RF antenna	5G/B5G IoT	7.81×10^{-11} ESA is achieved
Intelligent dynamic energy flow control algorithm [36]	2021	Electromagnetic wave	RF antenna	WSN	0.16 µV output per second
Rectenna array [37]	2020	Electromagnetic wave	RF antenna	IoT	67% of high energy conversion efficiency over Vivaldi rectenna
Hybrid spectrum access mode [38]	2020	Electromagnetic wave	RF antenna	Industrial IoT	Achieved larger transmission of data with less power
Broadband rectifier and a novel matching network [39]	2020	Electromagnetic wave	RF antenna	LTE	42% efficiency improvement
Supercapacitor with hybrid optimization [40]	2022	Hybrid solar, wind, and kinetic energy	Photovoltaic cell, wind turbine, and electromagnetic generator	Railway wireless sensors	2660 mW power generated from 5.5 m/s wind
Game theory and perturbed Lyapunov optimization theory [41]	2021	Hybrid vibration and kinetic energy	Piezoelectric and electromagnetic transducers	IoT	Better energy efficiency than naïve and greedy offloading
Parametric model optimization strategy [42]	2020	Hybrid vibration and kinetic energy	Piezoelectric and electromagnetic generators	IoT	25.45 mW power generated on 0.5G vibration
Rational adaptive mechanical design [43]	2022	Hybrid wind and kinetic energy	Triboelectric and electromagnetic generators	Wireless environment monitoring	60 times better output than the traditional model
Rotational tapered rollers [44]	2021	Hybrid wind and kinetic energy	Triboelectric and electromagnetic generators	IoT	63.8 mW output
Customized boxlike structure [45]	2020	Hybrid wind and kinetic energy	Triboelectric and electromagnetic nanogenerators	5G IoT	18.66 mW power output at 15 m/s wind speed
Magnetic flux intensity control [46]	2023	Magnetic field	Magneto-mechano-electric generator	WSN	5.5 mW power generated from 100e magnetic field
Energy per operation optimization [47]	2020	Solar	Photovoltaic cell	Wearable IoT	2.4 times better outcome than manual optimization
Boosted by boost converter [48]	2020	Solar	Photovoltaic cell	WSN	5.88 V generated at full sunlight
Efficient energy and radio resource management framework [49]	2020	Solar	Photovoltaic cell	UAV	Generated 13,000 J for 20 s

Table 3. *Cont.*

Methodology	Year	Energy Source	Generator Type	Application	Outcome
Prediction-based adaptive duty cycle MAC protocol [50]	2023	Solar	Photovoltaic cell	WSN	76.4% improvement on total energy consumption
Smart connector for energy balance [29]	2023	Thermal	Two thermoelectric generators	Bluetooth smart grid	4.9% energy improvement on sleep mode
Tapered nonlinear vibration energy harvester with MPPT [51]	2021	Vibration	Piezoelectric device	IoT	2660 $\mu W/cm^3 g^2$ of power density is obtained
Vibration enhancement mechanism [52]	2021	Vibration	Piezoelectric stack	IoT/WSN	2.622 W power output at 8.5 ms^{-1} wind speed
Cantilever and impact method [53]	2021	Vibration	Two piezoelectric devices	Zigbee wireless sensor	1.5 µW of maximum power output
Polymer film thickness alteration [54]	2022	Wind	Microwind generator	Wireless sensor	60 µW of maximum power output
In situ carbon dispersion method [55]	2022	Wind	High-power triboelectric nanogenerators	Wireless control	75.2 W/m^2 power density

Apart from optimized energy-generation techniques, certain optimization algorithms have been implemented in recent years to enhance the efficiency of energy utilization. A hybrid whale optimization algorithm–moth flame optimization was proposed to select the optimal cluster head for data transmission. It helps a wireless device to save its normalized network energy [56]. A slow-movement particle swarm optimization algorithm was designed to improve the scheduling process on a mobile edge device application. The experimental outcome indicates better computational and energy efficiency over the conventional particle swarm optimization [57]. A fuzzy-constraints-based cluster optimization methodology was developed to optimize the performances of cluster heads on data transmission in wireless ad hoc networks. The simulated outcome indicates a better network lifetime over the traditional LEACH and MPO methods [58]. An ad hoc on-demand multipath distance vector routing protocol was structured to enhance the energy efficiency in mobile ad hoc networks by enhancing the routing process. The performance of the proposed method gives better energy efficiency along with minimal data loss [59]. A machine-learning-based intelligent opportunistic routing protocol was proposed for WSN healthcare applications. The simulation result presents an acceptable outcome of energy consumption rate over the traditional MDOR and EEOR approaches [60].

6. Discussion on Emerging Methodologies

The literature section indicates that wireless devices are widely incorporated with RF antennas for extracting energy from electromagnetic waves. Following that, hybrid technologies are widely preferred for energy harvesting. In hybrid methods, wind with kinetic energy and vibration with kinetic energy are the most utilized methods. Electromagnetic generators are employed to convert kinetic energy into electrical energy, and piezoelectric sensors are utilized to convert vibration energy. Triboelectric nanogenerators and wind turbines are employed for harvesting energy from the wind. Individual solar-energy harvesting was found to be the third most preferred option; however, this was not found to be the focus of recent research studies in the way that electromagnetic wave energy generation has been studied.

The review work was performed to observe the research trends in energy harvesting in wireless devices, and therefore, the literature study was conducted between 2020 and 2023. Figure 4 represents the ratio of energy sources that were proposed for self-energy harvesting in wireless devices. Electromagnetic wave seems to be the topmost energy source, occupying 41.38% of space in the total self-sustainable models. Hybrid energy sources occupy 20.69% and solar energy takes 13.79% in the energy utilization space. Vibration and wind energy cover 10.34% and 6.9%, respectively. Magnetic field and thermal energy sources occupy each 3.45% of energy source space.

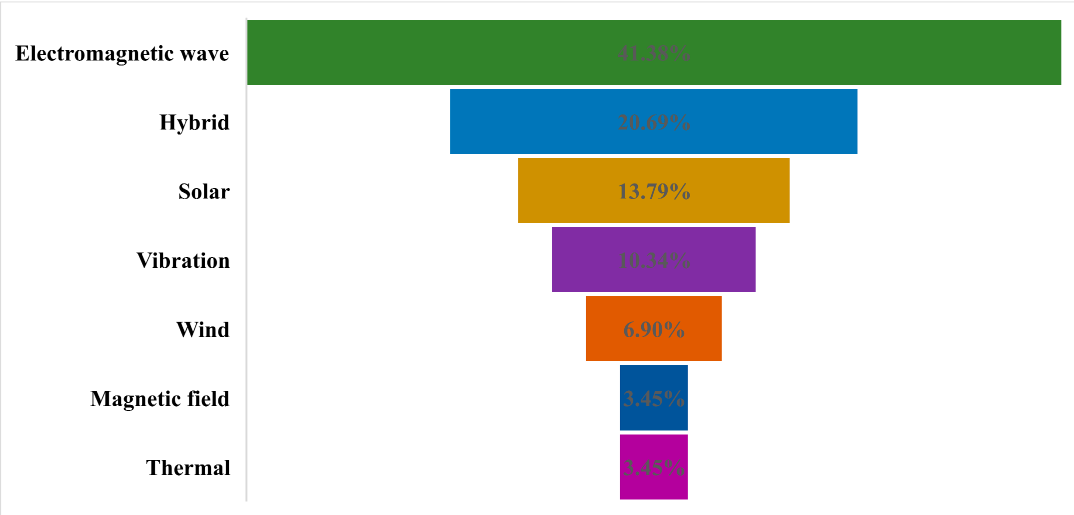

Figure 4. Distribution of energy source utilization by percentage.

Figure 5 represents the split-up proportion of the energy-harvesting generators utilized for wireless networks. It indicates the RF antenna as the most employed generator system in wireless devices. Wireless signals such as Wi-Fi, mobile, and other mobile communication have some low-level energy, and the RF antenna attracts such energy and stores it in a battery storage with the help of rectifier unit. In most of the wireless applications, the devices are structured with an RF antenna for signal transmission. The same RF antenna is utilized for energy harvesting in most of the systems [61]. Therefore, it does not require any additional energy-harvesting modules. Hence, it is widely used in wireless devices. Similar to RF antennae, an optical nanoantenna called a rectenna is also implemented in a few applications. However, its load power and energy conversion efficiency are comparatively poorer than other methods [62]. These kinds of self-harvesting methodologies may assist the Agriculture 4.0 methodologies, which are implemented with sensors and remote sensing units [63].

The electromagnetic generator seems to be the second most utilized power generator system in wireless devices. It creates electrical energy from flowing water and wind. However, the electromagnetic generator system cannot be placed in closed-environment wireless devices. It is majorly employed in open-place wireless communication systems. Similarly, the photovoltaic cell is also utilized in open-place wireless communication systems for harvesting energy from the solar energy source. However, the photovoltaic cell has the ability to generate only in the daytime. Hence, the solar energy source is utilized as one of the energy sources in hybrid systems. Piezoelectric sensors and triboelectric generators are also the most common models that are used in hybrid systems. The piezoelectric sensor generates electrical energy from vibrations, and the triboelectric generator generates electrical energy from wind energy. The wind turbine is also employed in a very few wireless devices for generating electrical energy. Table 4 represents the future directions and challenges of designing a self-energy-harvesting method for wireless applications.

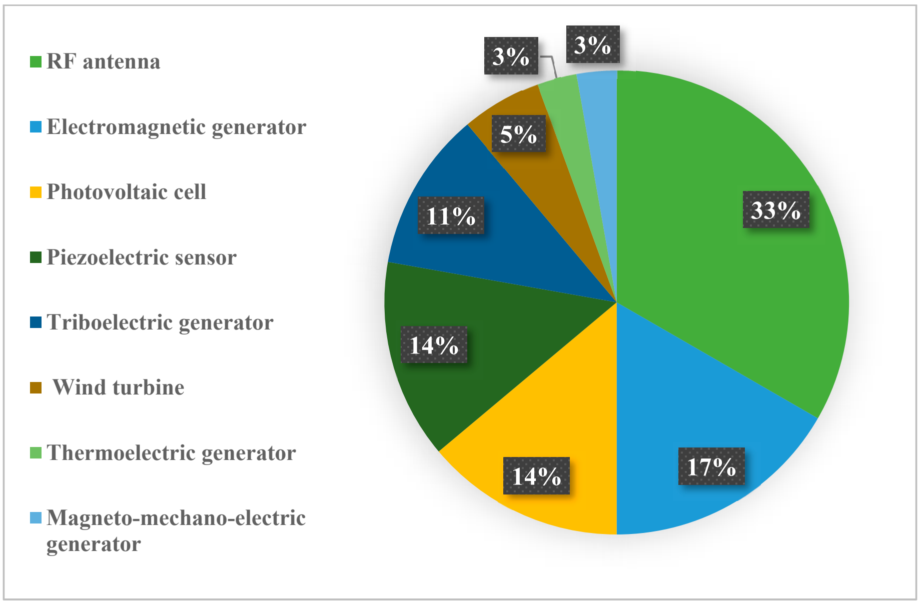

Figure 5. Distribution chart of preferred energy-harvesting generators.

Table 4. Future directions and challenges of self-energy-harvesting methods.

Methodology	Future Directions	Challenges
Electromagnetic wave	Minimizing the size of the RF antenna while maintaining its performance	General properties of the RF antenna material
Solar	Intelligent solar panel direction estimations	Space requirement and climate constraint
Vibration	Increasing the lifespan of the sensors	Cannot be suitable for several applications
Wind	Effienct windflow direction estimation	Climate constraint
Magnetic field	Improving the power density observation from the magnetic field	Not suitable for living area
Thermal	Increasing the energy conversion efficiency	Requires constant heat source

The performance of wireless energy-harvesting systems is measured in terms of power generated by them, and the following list indicates some of the other parameters that are used for estimation:

- Power conversion efficiency is a metric used for comparing a model with an existing technique [28].
- The performance of the self-harvesting wireless devices is optimized with an automatic algorithm, and in such cases, its performance is measured with the power requirement for some specific operation. The same operation is enforced in other algorithms, also for proving its efficiency [30,42,46].
- The energy optimization algorithms are also included in some wireless devices, and that reduces the pocket loss of signal transmission [29,32].
- Sleeping time analysis is found to be one of the efficient parameters, and that represents the amount of saved data transmission [29,34].
- Amount of power spent for sending a specific amount of data gives a better view of the wireless device in terms of its sustainability [38,43].

7. Conclusions

Next-generation wireless devices are expected to be incorporated with a self-energy-harvesting technique by many users. Therefore, different kinds of self-energy-harvesting methods have been developed in recent years. This paper explored the requirements of self-energy-harvesting systems in wireless devices, and it also indicated the methodologies that are widely employed in such energy-harvesting applications. A brief literature study was conducted with recent-years research outcomes from 2020 to 2023 to represent the recent trends in self-energy-harvesting techniques. The review summary indicated that electromagnetic-based power generation systems are widely employed in many applications, as they require very minimal peripheral modules for operation. The review also found that the research on solar-based power generation is not preferred by researchers in recent years for making energy-harvesting wireless devices, as it requires a huge amount of space. Similarly, thermal methodologies are not preferred, as these require a constant heat source; furthermore, wind-based methodologies were not preferred due to climatic considerations. The analysis explored the possible scope in future for a hybrid self-energy-harvesting system which may contain an RF antenna as a primary module for generating power from wireless signals. Other techniques such as photovoltaic, triboelectric, piezoelectric, and thermoelectric sensors can be equipped in such hybrid models based on the available energy source in the place where the wireless device is to be installed.

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References

1. He, C.; Chen, Y.-Y.; Phang, C.-R.; Stevenson, C.; Chen, I.-P.; Jung, T.-P.; Ko, L.-W. Diversity and Suitability of the State-of-the-Art Wearable and Wireless EEG Systems Review. *IEEE J. Biomed. Health Inform.* **2023**, 1–14. [CrossRef] [PubMed]
2. Rahmani, H.; Shetty, D.; Wagih, M.; Ghasempour, Y.; Palazzi, V.; Carvalho, N.B.; Correia, R.; Costanzo, A.; Vital, D.; Alimenti, F.; et al. Next-generation IoT devices: Sustainable eco-friendly manufacturing, energy harvesting, and wireless connectivity. *IEEE J. Microw.* **2023**, *3*, 237–255. [CrossRef]
3. Majid, M.; Habib, S.; Javed, A.R.; Rizwan, M.; Srivastava, G.; Gadekallu, T.R.; Lin, J.C.W. Applications of wireless sensor networks and internet of things frameworks in the industry revolution 4.0: A systematic literature review. *Sensors* **2022**, *22*, 2087. [CrossRef] [PubMed]
4. Yang, Z.; Chen, M.; Wong, K.K.; Poor, H.V.; Cui, S. Federated learning for 6G: Applications, challenges, and opportunities. *Engineering* **2022**, *8*, 33–41. [CrossRef]
5. Ananthi, J.V.; Jose, P.S.H. Performance Analysis of Clustered Routing Protocol for Wearable Sensor Devices in an IoT-Based WBAN Environment. In *Intelligent Technologies for Sensors: Applications, Design, and Optimization for a Smart World*; Apple Academic Press: Palm Bay, FL, USA, 2023; p. 253.
6. Tirth, V.; Alghtani, A.H.; Algahtani, A. Artificial intelligence enabled energy aware clustering technique for sustainable wireless communication systems. *Sustain. Energy Technol. Assess.* **2023**, *56*, 103028. [CrossRef]
7. Ouyang, Q.; Chen, J. The Future of Lithium-Ion Battery Charging Technologies. In *Advanced Model-Based Charging Control for Lithium-Ion Batteries*; Springer Nature: Singapore, 2023; pp. 175–176.
8. Cornet, B.; Fang, H.; Ngo, H.; Boyer, E.W.; Wang, H. An overview of wireless body area networks for mobile health applications. *IEEE Netw.* **2022**, *36*, 76–82. [CrossRef]
9. Mertes, J.; Lindenschmitt, D.; Amirrezai, M.; Tashakor, N.; Glatt, M.; Schellenberger, C.; Shah, S.M.; Karnoub, A.; Hobelsberger, C.; Yi, L.; et al. Evaluation of 5G-capable framework for highly mobile, scalable human-machine interfaces in cyber-physical production systems. *J. Manuf. Syst.* **2022**, *64*, 578–593. [CrossRef]
10. Li, L.; Liu, Y.; You, I.; Song, F. A Smart Retransmission Mechanism for Ultra-Reliable Applications in Industrial Wireless Networks. *IEEE Trans. Ind. Inform.* **2022**, *19*, 1988–1996. [CrossRef]

11. Vishnuram, P.; Nastasi, B. Wireless Chargers for Electric Vehicle: A Systematic Review on Converter Topologies, Environmental Assessment, and Review Policy. *Energies* **2023**, *16*, 1731. [CrossRef]
12. Wu, Y.; Song, Y.; Wang, T.; Qian, L.; Quek, T.Q.S. Non-orthogonal multiple access assisted federated learning via wireless power transfer: A cost-efficient approach. *IEEE Trans. Commun.* **2022**, *70*, 2853–2869. [CrossRef]
13. Xia, L.; Ma, S.; Tao, P.; Pei, W.; Liu, Y.; Tao, L.; Wu, Y. A Wind-Solar Hybrid Energy Harvesting Approach Based on Wind-Induced Vibration Structure Applied in Smart Agriculture. *Micromachines* **2022**, *14*, 58. [CrossRef] [PubMed]
14. Sayed, D.M.; Allam, N.K. All-solid-state, self-powered supercapacitors: State-of-the-art and future perspectives. *J. Energy Storage* **2022**, *56*, 105882. [CrossRef]
15. Hassan, M.; Abbas, G.; Li, N.; Afzal, A.; Haider, Z.; Ahmed, S.; Xu, X.; Pan, C.; Peng, Z. Significance of flexible substrates for wearable and implantable devices: Recent advances and perspectives. *Adv. Mater. Technol.* **2022**, *7*, 2100773. [CrossRef]
16. Verma, G.; Arora, S.; Nijhawan, G. A Solar, Thermal, and Piezoelectric Based Hybrid Energy Harvesting for IoT and Underwater WSN Applications. *Int. J. Sens. Wirel. Commun. Control* **2022**, *12*, 651–660. [CrossRef]
17. Chen, Y.; Zhao, F.; Lu, Y.; Chen, X. Dynamic task offloading for mobile edge computing with hybrid energy supply. *Tsinghua Sci. Technol.* **2022**, *28*, 421–432. [CrossRef]
18. Xiao, H.; Qi, N.; Yin, Y.; Yu, S.; Sun, X.; Xuan, G.; Liu, J.; Xiao, S.; Li, Y.; Li, Y. Investigation of Self-Powered IoT Sensor Nodes for Harvesting Hybrid Indoor Ambient Light and Heat Energy. *Sensors* **2023**, *23*, 3796. [CrossRef]
19. Kim, B.; Song, J.Y.; Kim, M.C.; Lin, Z.H.; Choi, D.; Park, S.M. All-aerosol-sprayed high-performance transparent triboelectric nanogenerator with embedded charge-storage layer for self-powered invisible security IoT system and raindrop-solar hybrid energy harvester. *Nano Energy* **2022**, *104*, 107878. [CrossRef]
20. Bakytbekov, A.; Nguyen, T.Q.; Zhang, G.; Strano, M.S.; Salama, K.N.; Shamim, A. Dual-function triple-band heatsink antenna for ambient RF and thermal energy harvesting. *IEEE Open J. Antennas Propag.* **2022**, *3*, 263–273. [CrossRef]
21. Kim, W.-G.; Kim, D.; Lee, H.M.; Choi, Y.-K. Wearable fabric-based hybrid energy harvester from body motion and body heat. *Nano Energy* **2022**, *100*, 107485. [CrossRef]
22. Yang, O.; Zhang, C.; Zhang, B.; He, L.; Yuan, W.; Liu, Y.; Li, X.; Zhou, L.; Zhao, Z.; Wang, J.; et al. Hybrid Energy-Harvesting System by a Coupling of Triboelectric and Thermoelectric Generator. *Energy Technol.* **2022**, *10*, 2101102. [CrossRef]
23. Bakytbekov, A.; Nguyen, T.Q.; Zhang, G.; Strano, M.S.; Salama, K.N.; Shamim, A. Synergistic multi-source ambient RF and thermal energy harvester for green IoT applications. *Energy Rep.* **2023**, *9*, 1875–1885. [CrossRef]
24. Zhao, L.C.; Zou, H.-X.; Zhao, Y.-J.; Wu, Z.-Y.; Liu, F.-R.; Wei, K.-X.; Zhang, W.-M. Hybrid energy harvesting for self-powered rotor condition monitoring using maximal utilization strategy in structural space and operation process. *Appl. Energy* **2022**, *314*, 118983. [CrossRef]
25. Bai, S.; Cui, J.; Zheng, Y.; Li, G.; Liu, T.; Liu, Y.; Hao, C.; Xue, C. Electromagnetic-triboelectric energy harvester based on vibration-to-rotation conversion for human motion energy exploitation. *Appl. Energy* **2023**, *329*, 120292. [CrossRef]
26. Liu, C.; Qu, G.; Shan, B.; Aranda, R.; Chen, N.; Li, H.; Zhou, Z.; Yu, T.; Wang, C.; Mi, J.; et al. Underwater hybrid energy harvesting based on TENG-MTEG for self-powered marine mammal condition monitoring system. *Mater. Today Sustain.* **2023**, *21*, 100301. [CrossRef]
27. Cheng, M.; Wu, J.; Liang, X.; Mao, R.; Huang, H.; Ju, D.; Hu, Z.; Guo, J.; Liu, M. Hybrid multi-mode magneto-mechano-electric generator with enhanced magnetic field energy harvesting performance. *Sens. Actuators A Phys.* **2023**, *352*, 114194. [CrossRef]
28. Li, J.; Gong, W. Optimized High-efficiency Multi-band RF Energy Harvester. In Proceedings of the 2023 IEEE Wireless Communications and Networking Conference (WCNC), Glasgow, UK, 26–29 March 2023; pp. 1–6.
29. Liu, Y.; Riba, J.-R.; Moreno-Eguilaz, M. Energy Balance of Wireless Sensor Nodes Based on Bluetooth Low Energy and Thermoelectric Energy Harvesting. *Sensors* **2023**, *23*, 1480. [CrossRef]
30. Raghav, K.S.; Bansal, D. Power controlled system for self-sustained RF energy harvesting sensors. *Analog. Integr. Circuits Signal Process.* **2022**, *113*, 73–79. [CrossRef]
31. Thangarajan, A.S.; Nguyen, T.D.; Liu, M.; Michiels, S.; Yang, F.; Man, K.L.; Ma, J.; Joosen, W.; Hughes, D. Static: Low Frequency Energy Harvesting and Power Transfer for the Internet of Things. *Front. Signal Process.* **2022**, *1*, 15. [CrossRef]
32. Shi, Z.; Xie, X.; Lu, H.; Yang, H.; Cai, J.; Ding, Z. Deep Reinforcement Learning-Based Multidimensional Resource Management for Energy Harvesting Cognitive NOMA Communications. *IEEE Trans. Commun.* **2021**, *70*, 3110–3125. [CrossRef]
33. Noghabaei, S.M.; Radin, R.L.; Savaria, Y.; Sawan, M. A high-sensitivity wide input-power-range ultra-low-power RF energy harvester for IoT applications. *IEEE Trans. Circuits Syst. I Regul. Pap.* **2021**, *69*, 440–451. [CrossRef]
34. Wang, Y.; Yang, K.; Wan, W.; Zhang, Y.; Liu, Q. Energy-efficient data and energy integrated management strategy for iot devices based on rf energy harvesting. *IEEE Internet Things J.* **2021**, *8*, 13640–13651. [CrossRef]
35. Amjad, M.; Chughtai, O.; Naeem, M.; Ejaz, W. SWIPT-assisted energy efficiency optimization in 5G/B5G cooperative IoT network. *Energies* **2021**, *14*, 2515. [CrossRef]
36. Verma, G.; Sharma, V. A novel RF energy harvester for event-based environmental monitoring in Wireless Sensor Networks. *IEEE Internet Things J.* **2021**, *9*, 3189–3203. [CrossRef]
37. Song, C.; Lu, P.; Shen, S. Highly efficient omnidirectional integrated multiband wireless energy harvesters for compact sensor nodes of Internet-of-Things. *IEEE Trans. Ind. Electron.* **2020**, *68*, 8128–8140. [CrossRef]
38. Liu, X.; Hu, S.; Li, M.; Lai, B. Energy-efficient resource allocation for cognitive industrial Internet of Things with wireless energy harvesting. *IEEE Trans. Ind. Inform.* **2020**, *17*, 5668–5677. [CrossRef]

39. Wang, M.; Yang, L.; Shi, Y. A dual-port microstrip rectenna for wireless energy harvest at LTE band. *AEU-Int. J. Electron. Commun.* **2020**, *126*, 153451. [CrossRef]
40. Tairab, A.M.; Wang, H.; Hao, D.; Azam, A.; Ahmed, A.; Zhang, Z. A hybrid multimodal energy harvester for self-powered wireless sensors in the railway. *Energy Sustain. Dev.* **2020**, *68*, 150–169. [CrossRef]
41. Xia, S.; Yao, Z.; Li, Y.; Mao, S. Online distributed offloading and computing resource management with energy harvesting for heterogeneous MEC-enabled IoT. *IEEE Trans. Wirel. Commun.* **2021**, *20*, 6743–6757. [CrossRef]
42. Jung, I.; Choi, J.; Park, H.-J.; Lee, T.-G.; Nahm, S.; Song, H.-C.; Kim, S.; Kang, C.-Y. Design principles for coupled piezoelectric and electromagnetic hybrid energy harvesters for autonomous sensor systems. *Nano Energy* **2020**, *75*, 104921. [CrossRef]
43. Lee, D.; Cho, S.; Jang, S.; Ra, Y.; Jang, Y.; Yun, Y.; Choi, D. Toward effective irregular wind energy harvesting: Self-adaptive mechanical design strategy of triboelectric-electromagnetic hybrid wind energy harvester for wireless environmental monitoring and green hydrogen production. *Nano Energy* **2022**, *102*, 107638. [CrossRef]
44. Fang, Y.; Tang, T.; Li, Y.; Hou, C.; Wen, F.; Yang, Z.; Chen, T.; Sun, L.; Liu, H.; Lee, C. A high-performance triboelectric-electromagnetic hybrid wind energy harvester based on rotational tapered rollers aiming at outdoor IoT applications. *iScience* **2021**, *24*, 102300. [CrossRef] [PubMed]
45. Fan, X.; He, J.; Mu, J.; Qian, J.; Zhang, N.; Yang, C.; Hou, X.; Geng, W.; Wang, X.; Chou, X. Triboelectric-electromagnetic hybrid nanogenerator driven by wind for self-powered wireless transmission in Internet of Things and self-powered wind speed sensor. *Nano Energy* **2020**, *68*, 104319. [CrossRef]
46. Patil, D.R.; Lee, S.; Thakre, A.; Kumar, A.; Song, H.; Jeong, D.-Y.; Ryu, J. Boosting the energy harvesting performance of cantilever structured magneto-mechano-electric generator by controlling magnetic flux intensity on magnet proof mass. *J. Mater.* 2023, *in press*. [CrossRef]
47. Park, J.; Bhat, G.; Nk, A.; Geyik, C.S.; Ogras, U.Y.; Lee, H.G. Energy per operation optimization for energy-harvesting wearable IoT devices. *Sensors* **2020**, *20*, 764. [CrossRef] [PubMed]
48. Antony, S.M.; Indu, S.; Pandey, R. An efficient solar energy harvesting system for wireless sensor network nodes. *J. Inf. Optim. Sci.* **2020**, *41*, 39–50. [CrossRef]
49. Zhang, J.; Lou, M.; Xiang, L.; Hu, L. Power cognition: Enabling intelligent energy harvesting and resource allocation for solar-powered UAVs. *Future Gener. Comput. Syst.* **2020**, *110*, 658–664. [CrossRef]
50. Sarang, S.; Stojanović, G.M.; Drieberg, M.; Stankovski, S.; Bingi, K.; Jeoti, V. Machine Learning Prediction Based Adaptive Duty Cycle MAC Protocol for Solar Energy Harvesting Wireless Sensor Networks. *IEEE Access* **2023**, *11*, 17536–17554. [CrossRef]
51. Paul, K.; Amann, A.; Roy, S. Tapered nonlinear vibration energy harvester for powering Internet of Things. *Appl. Energy* **2021**, *283*, 116267. [CrossRef]
52. Sheeraz, M.A.; Malik, M.S.; Rehman, K.; Elahi, H.; Butt, Z.; Ahmad, I.; Eugeni, M.; Gaudenzi, P. Numerical assessment and parametric optimization of a piezoelectric wind energy harvester for IoT-based applications. *Energies* **2021**, *14*, 2498. [CrossRef]
53. Kim, J.H.; Cho, J.Y.; Jhun, J.P.; Song, G.J.; Eom, J.H.; Jeong, S.; Hwang, W.; Woo, M.S.; Sung, T.H. Development of a hybrid type smart pen piezoelectric energy harvester for an IoT platform. *Energy* **2021**, *222*, 119845. [CrossRef]
54. Le Scornec, J.; Guiffard, B.; Seveno, R.; Le Cam, V.; Ginestar, S. Self-powered communicating wireless sensor with flexible aero-piezoelectric energy harvester. *Renew. Energy* **2022**, *184*, 551–563. [CrossRef]
55. Zhang, Z.; Zhang, Q.; Zhou, Z.; Wang, J.; Kuang, H.; Shen, Q.; Yang, H. High-power triboelectric nanogenerators by using in-situ carbon dispersion method for energy harvesting and self-powered wireless control. *Nano Energy* **2022**, *101*, 107561. [CrossRef]
56. Maddikunta, P.K.R.; Gadekallu, T.R.; Kaluri, R.; Srivastava, G.; Parizi, R.M.; Khan, M.S. Green communication in IoT networks using a hybrid optimization algorithm. *Comput. Commun.* **2020**, *159*, 97–107. [CrossRef]
57. Zhang, Y.; Liu, Y.; Zhou, J.; Sun, J.; Li, K. Slow-movement particle swarm optimization algorithms for scheduling security-critical tasks in resource-limited mobile edge computing. *Future Gener. Comput. Syst.* **2020**, *112*, 148–161. [CrossRef]
58. Mohammed, A.S.; Asha, S.B.P.N.; Venkatachalam, K. FCO—Fuzzy constraints applied cluster optimization technique for wireless adhoc networks. *Comput. Commun.* **2020**, *154*, 501–508. [CrossRef]
59. Bhardwaj, A.; El-Ocla, H. Multipath routing protocol using genetic algorithm in mobile ad hoc networks. *IEEE Access* **2020**, *8*, 177534–177548. [CrossRef]
60. Pham, Q.-V.; Mirjalili, S.; Kumar, N.; Alazab, M.; Hwang, W.-J. Whale optimization algorithm with applications to resource allocation in wireless networks. *IEEE Trans. Veh. Technol.* **2020**, *69*, 4285–4297. [CrossRef]
61. Sherazi, H.H.R.; Zorbas, D.; O'flynn, B. A comprehensive survey on RF energy harvesting: Applications and performance determinants. *Sensors* **2022**, *22*, 2990. [CrossRef]
62. Citroni, R.; Di Paolo, F.; Livreri, P. Evaluation of an optical energy harvester for SHM application. *AEU-Int. J. Electron. Commun.* **2019**, *111*, 152918. [CrossRef]
63. Barrile, V.; Simonetti, S.; Citroni, R.; Fotia, A.; Bilotta, G. Experimenting Agriculture 4.0 with Sensors: A Data Fusion Approach between Remote Sensing, UAVs and Self-Driving Tractors. *Sensors* **2022**, *22*, 7910. [CrossRef]