International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 15, Issue 3 [March 2026] PP: 142-152

Energy Harvesting Techniques for Low-Power Devices: A review of the Performance, Challenges, and Sustainability Implications

John-Okere Franklin and Orakwue Stella
Department of Electrical / Electronic Engineering, Faculty of Engineering. University of Port Harcourt, PMB 5323, Choba, Port Harcourt, Rivers State, Nigeria

ABSTRACT: *Energy harvesting (EH) has emerged as a key enabler for sustainable, low-power electronic systems, particularly in the context of wireless sensor networks (WSNs) and Internet of Things (IoT) devices. This paper presents a comprehensive review of existing EH techniques, including photovoltaic, mechanical, thermal, radio-frequency, bioenergy, and human energy harvesting, with an emphasis on their comparative performance, influencing factors, and environmental contributions. The study examines critical design considerations such as transduction mechanisms, power management strategies, and material selection, highlighting their impact on system efficiency, reliability, and scalability. Hybrid EH systems are identified as a promising approach to overcome the limitations of single-source harvesting, providing stable and scalable power across diverse operational environments. Furthermore, the role of EH in reducing battery dependence, minimizing electronic waste, and supporting global sustainability and climate change mitigation goals is discussed. Key research gaps, including limited large-scale deployments, material durability challenges, low conversion efficiency, and the absence of standardized evaluation frameworks, are identified. The paper concludes by proposing future research directions focused on hybrid system optimization, advanced material development, and standardized performance assessment to advance EH from niche applications to mainstream, self-powered electronics.*

Date of Submission: 15-03-2026 Date of acceptance: 31-03-2026

I. INTRODUCTION

The rapid expansion of low-power electronic devices has transformed modern society, enabling applications ranging from industrial monitoring and healthcare to smart homes and smart cities. Central to this transformation is the Internet of Things (IoT), which relies on vast networks of wireless sensor nodes. Analysts anticipate a “Trillion Sensor Universe,” in which billions of devices are deployed annually to support communication, automation, and environmental monitoring [4]1. The success of such systems, however, depends critically on the availability of reliable and sustainable power supply solutions. Conventional batteries, although widely used, face significant limitations when applied at this scale. Frequent battery replacement is impractical, particularly for devices located in remote or inaccessible environments, and contributes to increasing environmental waste. Even advanced energy storage technologies, such as lithium-ion batteries and supercapacitors, remain constrained by finite lifespans, safety concerns, and environmental impact [11]2. These challenges have intensified interest in energy harvesting (EH), which involves capturing ambient energy from the surrounding environment and converting it into usable electrical power [7]–[9]. 3,4,5

Energy harvesting technologies draw from diverse sources, including sunlight, mechanical vibrations, thermal gradients, radio-frequency signals, and biochemical processes. Unlike conventional power supply methods, EH offers the potential for long-term autonomy, reduced maintenance requirements, and improved sustainability for low-power electronic devices. Although the harvested power levels are typically modest—ranging from microwatts to a few watts depending on the energy source and operating conditions—these levels are sufficient for many IoT and wireless sensor applications [14]6. Consequently, EH is not intended to replace batteries outright, but rather to complement them, extend their operational lifetimes, and reduce dependence on conventional power infrastructure [15]7.

The academic and industrial communities have responded with extensive research into EH mechanisms, materials, and system architectures. These efforts have led to significant advances in photovoltaic cells, piezoelectric materials, thermoelectric semiconductors, and hybrid energy harvesting approaches [6]8, [9]5, [22]9, [34]10. Beyond technical performance improvements, the relevance of EH extends to environmental sustainability. By reducing reliance on battery production and disposal, energy harvesting technologies contribute to climate change mitigation efforts and align with global sustainability goals across multiple sectors [1]–[3].11,12,13

Despite these advances, several challenges remain. Energy conversion efficiencies are often low, harvested energy is inherently intermittent, and successful integration into practical systems requires careful consideration of power management strategies and material durability. Moreover, the lack of standardized evaluation methods makes direct comparison across different EH systems difficult. These limitations highlight the need for comprehensive evaluations that synthesize existing knowledge and identify promising directions for future research and application.

This paper evaluates existing energy harvesting techniques for low-power device applications with the following objectives:

1. To examine the range of ambient energy sources and the techniques used to harvest them.
2. To assess the factors influencing EH performance, including transduction mechanisms, power management strategies, and material properties.
3. To discuss the broader role of EH in enabling sustainable technology and mitigating environmental impact.

By addressing these objectives, the study contributes to ongoing efforts to develop self-sustaining electronic systems capable of meeting the demands of large-scale deployment in the IoT era.

II. ENERGY HARVESTING

Energy and power remain fundamental considerations in the design of electronic devices, as every electronic circuit requires a stable energy supply for effective operation. As societies adopt increasingly sophisticated technologies, the demand for low-power devices has grown at an unprecedented pace. This growth is particularly evident in the rapid expansion of the Internet of Things (IoT) and pervasive sensing networks. Researchers project the advent of a “Trillion Sensor Universe,” in which networks comprising up to one trillion sensor nodes are deployed annually to support applications in healthcare, environmental monitoring, industrial automation, and smart cities [4]1. At such a massive scale, powering each node with conventional batteries is neither cost-effective nor sustainable. Frequent battery replacement is impractical, especially for devices located in remote or inaccessible environments, and introduces additional challenges related to maintenance and environmental waste [4]1.

This challenge highlights the importance of energy harvesting (EH), which refers to the process of capturing ambient energy from the surrounding environment and converting it into usable electrical energy [7]–[9]3,4,5. EH enables the design of electronic devices that can operate autonomously with minimal human intervention, thereby improving sustainability and system reliability. By converting energy from diverse sources such as solar radiation, mechanical vibrations, temperature gradients, radio-frequency (RF) signals, and even biological processes, EH supports long-term device operation while reducing dependence on finite energy storage technologies such as batteries [7]3.

The adoption of EH technologies is particularly relevant in applications where battery-powered solutions are limited by capacity, weight, or cost. For example, advanced lithium-ion batteries and supercapacitors remain constrained in terms of energy density, long-term stability, and environmental impact [11]. Consequently, EH has emerged not as a complete replacement for energy storage devices, but as a complementary technology that enhances system efficiency and extends operational lifetime [14], [15]. The primary objectives of energy harvesting include:

- Extending device lifespan,
- Reducing or eliminating reliance on wired infrastructure,
- Minimizing or replacing battery dependence,
- Enhancing performance while lowering maintenance requirements,
- Simplifying installation and deployment,
- Lowering total cost of ownership, and
- Reducing environmental waste [3].

Depending on the application, harvested energy can either be consumed immediately or stored for later use, resulting in two primary system architectures: Harvest-Use and Harvest-Store-Use [7], [13]. In the Harvest-Use model, devices draw power directly from the harvested energy, which is feasible in environments where the energy source is reliable and continuous. In contrast, the Harvest-Store-Use model stores energy in an intermediate storage element, such as a supercapacitor or rechargeable battery, before supplying it to the device. This architecture ensures continuous operation even when ambient energy availability fluctuates.

Although EH shares conceptual similarities with large-scale renewable energy generation, the operational scale is significantly smaller. The power produced typically ranges from microwatts to a few watts [14]. For this reason, EH does not fully replace batteries but enhances their performance, particularly in applications where device accessibility is limited and maintenance costs are high [14], [15]. Liu et al. [12] presented a timeline of key milestones in the development of EH, illustrating its strong correlation with the evolution of low-power devices. This progression demonstrates how advances in EH have directly responded to the growing demand for autonomous and long-lasting electronic systems.

ENERGY HARVESTING TECHNOLOGY AND LOW-POWER DEVICES

The operational lifetime of wireless networks is one of the most critical considerations in the design of low-power devices. In wireless sensor networks (WSNs), power availability largely determines how long sensor nodes can remain active before requiring replacement or maintenance. Energy harvesting is therefore integral to the development of WSNs and related systems, such as machine condition monitoring (MCM) platforms widely used in industrial environments. For example, WSN-based MCM systems offer more robust and autonomous monitoring than wired systems, as EH-enabled nodes can operate independently without reliance on bulky batteries or extensive cabling [3], [13], [14].

The expansion of machine-to-machine (M2M) communication has further accelerated EH research. Smart factories, offices, and homes increasingly depend on autonomous sensors that interact with other systems in real time. To sustain these systems, designers are integrating EH solutions that improve energy efficiency, extend device lifetime, and ensure reliable operation even under harsh environmental conditions [13], [14].

Mateu and Moll [15] linked EH development to advances in batteries and microelectronics. They explained that as integrated circuits follow Moore's law—shrinking transistor sizes and reducing supply voltages—the overall energy consumption of electronic devices decreases. For a scaling factor α ($\alpha > 1$), the energy consumed by a scaled circuit decreases according to $(1/\alpha)^3$. When devices operate at maximum performance, improvements in transistor design reduce service time, resulting in an energy scaling closer to $(1/\alpha)^2$. In constant-service applications, the scaling remains approximately $(1/\alpha)^3$ [15]. These scaling laws highlight how device miniaturization and EH technologies can co-evolve to achieve higher efficiency.

Several researchers emphasize the importance of incorporating EH at the early stages of system design. Chitechi and Odoyo [16] identified three major research areas for alternative mobile power supplies: photovoltaics, fuel cells, and thermoelectric or piezoelectric systems. They argued that alternative energy sources for ICT devices must be considered during initial design rather than introduced as an afterthought. Sanislav et al. [13] reinforced this view, asserting that energy efficiency should be treated as a core design paradigm for low-power systems.

The integration of EH is also closely linked to the concept of self-sustainable technology. Calautit et al. [11] conducted a comprehensive review of micro-scale EH systems and concluded that maximum efficiency can only be achieved when energy harvesters, energy storage devices, and power management systems are designed as interconnected components rather than in isolation. Their analysis showed that combining EH with energy storage and intelligent power management significantly improves device performance while ensuring long-term sustainability.

Furthermore, Ahmad et al. [14] and Elahi et al. [7] observed that the reliability of EH technologies depend heavily on environmental durability and material selection. Since many WSN and IoT devices operate in hostile environments such as industrial plants or outdoor monitoring stations EH systems must withstand mechanical stress, temperature variations, and electromagnetic interference. Advances in material science and transduction mechanisms, including piezoelectric composites, thermoelectric semiconductors, and improved photovoltaic materials, play a decisive role in enabling more efficient and reliable energy harvesters [6], [9], [22].

In summary, the interdependence between EH technologies and low-power devices is evident. The miniaturization of electronics and the demand for autonomous operation have driven parallel advances in EH. Today, EH not only complements battery-based systems but also enables applications that would otherwise be impractical due to energy constraints. As different EH techniques are suited to different functionalities, the following sections discuss energy sources and harvesting methods in greater detail.

ENERGY SOURCES

Energy harvesting involves converting ambient energy into usable electrical energy for low-power devices [10]. Available energy sources vary widely and are commonly classified into environmental and human-derived sources [15]. Environmental sources include solar radiation, mechanical vibrations, thermal gradients, and electromagnetic waves, while human-derived sources involve body motion, body heat, and biochemical processes [12]. Although researchers classify these sources differently depending on research focus, the classifications remain broadly related, as they ultimately describe the origin of the harvested energy [14], [17]–[20].

The most frequently reported energy sources in the literature include electromagnetic radiation (solar and RF), mechanical energy, human energy, bioenergy, thermal gradients, and hybrid sources. Each source exhibits unique characteristics that influence its suitability for powering low-power devices. Solar and RF energy are attractive due to their availability, while mechanical and thermal sources are often abundant in industrial and environmental monitoring contexts. Bioenergy and human-based sources, though less mature, offer innovative opportunities for self-sustaining healthcare and wearable systems [12], [13].

For the purpose of this study, five key categories are considered: electromagnetic radiation, mechanical energy, human energy, bioenergy, and hybrid sources. These categories form the basis for evaluating specific harvesting techniques and their applicability in powering devices deployed in challenging or remote environments.

ENERGY HARVESTING TECHNIQUES

The techniques used to harvest ambient energy influence not only the categorization of energy sources but also the design of energy storage systems and the overall performance of low-power devices in practical applications. The literature consistently emphasizes that reliable materials, robust device structures, and efficient transduction mechanisms are essential for sustained operation, particularly in harsh or inaccessible environments [12]. By reducing reliance on wired power connections and frequent battery replacement, energy harvesting technologies enhance system autonomy, environmental sustainability, and long-term cost efficiency [4], [21].

Human Energy Harvesting

The human body continuously generates energy in the form of heat and motion, much of which remains unused. Human energy harvesting seeks to convert this otherwise wasted energy into electrical power, providing a renewable and alternative energy source for low-power devices [13], [22]. Human energy harvesting generally exploits three main sources: biochemical, biomechanical, and thermal energy.

Biochemical energy harvesting is achieved through biofuel cells, which utilize chemical reactions within the human body to generate electricity. Two primary types of biofuel cells have been developed: enzymatic fuel cells (EFCs) and microbial fuel cells (MFCs). EFCs employ enzyme catalysts to facilitate oxidation–reduction reactions, whereas MFCs rely on microorganisms to produce electrical energy [22]. These approaches show promise for implantable and wearable medical devices, although their output power remains relatively low.

Thermal energy harvesting from the human body exploits heat generated through metabolic processes such as digestion, blood circulation, and muscle activity. Thermoelectric generators (TEGs) convert temperature differences between the human body and the surrounding environment into electrical power [20], [23]. Two dominant approaches are reported: thermoelectric energy harvesters (TEEHs), which rely on spatial temperature gradients, and pyroelectric energy harvesters (PEEHs), which depend on temporal temperature fluctuations. Because human body temperature is relatively stable, PEEHs are often combined with other harvesting mechanisms to enhance reliability [13].

Biomechanical energy harvesting, derived from human motion, represents one of the most promising approaches for wearable and implantable devices. Daily activities such as walking, arm movement, and interaction with objects generate kinetic energy that can be converted into electrical energy. Common conversion techniques include electromagnetic, electrostatic, piezoelectric, and triboelectric harvesting [19], [23], [24]. Among these, piezoelectric and triboelectric harvesters have demonstrated strong potential due to their ability to convert irregular and low-frequency motions into usable power [24].

Overall, human energy harvesting provides low but continuous power, making it suitable for biomedical and wearable applications. However, challenges remain in improving efficiency, miniaturization, and integration with flexible and biocompatible materials [22].

Bioenergy Harvesting

Bioenergy harvesting extends beyond human-derived sources to include energy obtained from plants, soil, and aquatic environments. Although still an emerging field, bioenergy harvesting presents significant opportunities for agricultural and environmental monitoring applications.

Plant-based energy harvesting systems, for example, exploit microbial activity in soil to generate electricity, enabling the deployment of sensor nodes for monitoring parameters such as soil moisture, temperature, and humidity [13]. Karan et al. [25] proposed soil-based energy harvesters capable of powering wireless sensors, thereby eliminating the need for battery replacement in remote agricultural environments.

Another notable approach is blue energy harvesting, which extracts energy from salinity gradients in marine and estuarine environments. Blue energy is abundant and has been identified as one of the most efficient renewable energy sources at large scales [12]. Recent studies have explored its application in self-sustaining coastal and ocean-monitoring systems [26], [27]. Related applications include fish-tagging devices, where sensors are powered by energy harvested from water flow and fish movement [9].

Wave energy harvesting is also gaining attention. Viet et al. [28] developed a floating piezoelectric-based wave energy harvester capable of producing outputs of up to 103 W in simulations. Although still largely experimental, such results demonstrate the considerable potential of aquatic environments for powering remote monitoring systems.

Despite their sustainability advantages, bioenergy harvesters are often location-dependent and require robust designs capable of withstanding environmental stressors such as corrosion, biofouling, and mechanical fatigue.

Thermal Energy Harvesting

Thermal energy harvesting exploits temperature differences or temporal heat variations to generate electrical power. Ambient thermal energy is widely available from industrial equipment, natural temperature gradients, and waste heat generated by mechanical and electrical processes [14], [20].

Thermal harvesting primarily relies on thermoelectric and pyroelectric effects. The Seebeck, Peltier, and Thomson effects describe the generation of electrical voltage in response to thermal gradients across materials [19], [22]. Thermoelectric generators (TEGs) utilize these principles, with performance largely dependent on the temperature difference between hot and cold junctions [19]. Pyroelectric devices, in contrast, generate electricity from time-varying temperature changes.

Industrial environments are particularly well suited for thermal energy harvesting due to the abundance of waste heat from furnaces, kilns, dryers, and power plants [20]. Modeling studies by Akinaga [4] and Davidson and Mo [5] emphasized the importance of optimizing material properties and device geometry to enhance the Seebeck coefficient and overall conversion efficiency.

While thermal energy harvesters are reliable in high-temperature environments, their efficiency declines significantly under low temperature gradients. Nevertheless, they remain attractive for powering industrial sensors and off-grid monitoring systems where waste heat is readily available.

Electromagnetic Radiation Energy Harvesting

Electromagnetic radiation constitutes a versatile and widely available energy source, with two principal subcategories: radio-frequency (RF) energy harvesting and photovoltaic (PV) energy harvesting.

- *RF Energy Harvesting*

RF energy harvesting exploits electromagnetic waves emitted by communication infrastructures such as cellular base stations, Wi-Fi routers, broadcast transmitters, and satellites. RF signals are pervasive and accessible in both indoor and outdoor environments, making them attractive for powering low-power devices in urban and semi-urban settings [13], [19].

However, efficient RF energy harvesting requires large, broadband, and high-gain antennas, which may increase system complexity and size [29]. Performance is also affected by environmental factors such as distance from transmitters, signal attenuation, and network congestion [19]. Despite these limitations, RF energy harvesting supports important applications including wireless body area networks (WBANs), machine-to-gateway communication, and cyber-physical systems [3], [7], [10].

A key advantage of RF harvesting is its ability to provide continuous energy independent of weather conditions or mechanical motion. Furthermore, RF signals enable wireless power transfer, which holds promise for future seamless energy delivery to distributed low-power devices [30].

- *Photovoltaic Energy Harvesting*

Solar energy remains the most mature and widely deployed energy harvesting technique. The Earth receives approximately 173×1012173 \times 10^{12}173×1012 kW of solar energy continuously, far exceeding global energy consumption [13]. Photovoltaic (PV) systems convert solar radiation directly into electrical energy and are suitable for both indoor and outdoor applications.

PV harvesting has been extensively applied to wireless sensor networks, IoT devices, and portable electronics [13], [14]. Its key advantages include high energy availability, technological maturity, and scalability. Indoor PV cells designed for low-light conditions can operate under artificial illumination, although their efficiency is generally lower than that of outdoor PV systems [3].

The primary limitation of PV harvesting is its dependence on lighting and weather conditions, which reduces reliability in environments with limited or fluctuating light [31], [32]. Hybridization with other harvesting methods is often employed to address this limitation.

Mechanical Energy Harvesting

Mechanical energy harvesting utilizes energy from vibrations, pressure variations, acoustic waves, and kinetic motion. Mechanical energy sources are abundant in environments such as industrial machinery, vehicles, infrastructure, and human activities [13], [14].

Vibration-based energy harvesters are among the most widely studied mechanical harvesters.

Electromagnetic vibration harvesters, for example, have been integrated into machine condition monitoring systems to power wireless sensor nodes [33]. Piezoelectric and triboelectric harvesters are also effective in converting irregular mechanical motion into electrical energy, offering compact solutions for industrial and environmental applications [3].

Mechanical energy harvesters typically provide higher energy density than many other harvesting techniques and are particularly useful in indoor or overcast environments where solar energy is limited. However, their output is often intermittent, as it depends on the presence and frequency of mechanical excitation.

Hybrid Energy Harvesting

Hybrid energy harvesting combines two or more energy sources or transduction mechanisms to improve reliability and energy availability. Since no single energy source is consistently available across all environments, hybrid systems ensure continuous operation when one source becomes unavailable [3].

Hybrid harvesters can be classified as multi-source systems (e.g., solar–thermal or vibration–acoustic) or multi-mechanism systems (e.g., piezoelectric–electromagnetic combinations) [14]. Bai et al. [34] demonstrated a hybrid harvester combining vibration and thermal energy for wireless sensor nodes, while Demir et al. [35] reported hybrid biomedical harvesters integrating multiple mechanisms to power implantable medical devices.

Hybrid systems are increasingly regarded as the most promising approach for future low-power applications. Their ability to leverage complementary energy sources enhances reliability and reduces dependence on batteries. Nevertheless, challenges remain in terms of circuit complexity, system size, and efficiency trade-offs [14], [35].

TABLE 1. COMPARATIVE SUMMARY OF ENERGY HARVESTING TECHNIQUES

Technique / Source	Typical Power Output	Key Advantages	Limitations	Applications
Human Energy (motion/heat)	µW – mW	Continuous, suitable for wearables	Low power, complex integration	Wearables, medical implants
Bioenergy (plants/water)	mW – 100 W (waves)	Sustainable, location-specific sources	Environmental dependence	Agriculture, marine sensors
Thermal Energy (TEGs)	µW – W	Reliable in industrial settings	Efficiency depends on gradients	Industrial monitoring, IoT
RF Harvesting	µW – mW	Ubiquitous, continuous, wireless power	Low density, antenna requirements	WBANs, IoT, smart homes
Photovoltaics (PV)	mW – W	Mature, abundant source	Weather/light dependent	IoT, WSNs, outdoor devices
Mechanical Energy	µW – mW	High density, abundant in industry	Intermittent, environment specific	Industrial/structural sensors
Hybrid Systems	mW – W	Reliable, flexible, future-proof	Complexity, integration challenges	IoT, biomedical, smart systems

2.4 Factors That Influence Energy Harvesting Techniques

The effectiveness of energy harvesting technologies for low-power device applications depends not only on the selected energy source but also on several interrelated factors. The literature reviewed in this study identifies **transduction mechanisms**, **power management strategies**, and **material selection** as critical determinants of EH performance. These factors influence conversion efficiency, energy stability, scalability, and long-term reliability, and are widely recognized as key areas for continued research and optimization [3], [7], [11], [13].

2.4.1 Transduction Mechanisms

Transduction mechanisms convert ambient energy into electrical energy and form the core of any energy harvesting system. Their efficiency directly determines the feasibility of EH in practical applications. Ibrahim et al. [3] demonstrated how mathematical models describe the operating principles of mechanisms such as piezoelectric, thermoelectric, and electromagnetic transduction. Elahi et al. [7] further emphasized that EH techniques and transduction mechanisms are inherently linked, as the mechanism defines how energy is captured and converted.

Thermoelectric transduction relies on the Seebeck effect to generate voltage from temperature gradients, while piezoelectric transduction converts mechanical stress into electrical charge. Electromagnetic transduction, in contrast, exploits relative motion between conductors and magnetic fields [20], [22]. Each mechanism presents distinct advantages and limitations. Piezoelectric harvesters are compact and sensitive to vibration but generally produce low power. Electromagnetic harvesters can deliver higher output power but typically require larger device dimensions. Thermoelectric harvesters perform reliably in industrial settings but suffer reduced efficiency at low temperature gradients [22].

The choice of transduction mechanism also affects system integration. Wearable applications often favor piezoelectric or triboelectric mechanisms due to their flexibility and low weight, whereas industrial systems typically employ thermoelectric or electromagnetic mechanisms because of higher available energy densities [11], [23]. Andrade [9] noted that some studies classify EH systems directly by transduction mechanism rather than energy source, underscoring the close relationship between the two.

Power Management

Effective power management is essential to ensure that harvested energy is stored and delivered efficiently to the load. Power management circuits regulate voltage and current, minimize conversion losses, and match impedance between the harvester, storage element, and device. Elahi et al. [7] described power management as one of the most critical components of EH systems, noting that poor regulation can render harvested energy unusable.

Sanislav et al. [13] reviewed various power management strategies and highlighted modeling techniques for optimizing circuit design. A major challenge arises from the high internal impedance of many EH sources, which leads to impedance mismatch when interfaced with storage devices or sensors. Niu et al. [36] reported that this issue is particularly pronounced at low frequencies, where harvested energy is limited.

Calautit et al. [11] emphasized that self-sustainable systems require a holistic design approach in which EH, energy storage, and intelligent power management are integrated. Their findings demonstrated that such integration significantly improves system efficiency, extends operational lifetime, and reduces energy losses. Ahmad et al. [14] similarly identified power management as a core element of EH system architecture.

Common power management techniques include maximum power point tracking (MPPT) for photovoltaic systems, low-dropout regulators for voltage stabilization, and energy-aware scheduling for wireless sensor nodes. Ultimately, effective power management determines whether an EH system can operate reliably under real-world conditions.

Materials

Material selection plays a decisive role in the performance, durability, and adaptability of energy harvesting systems. Advances in material science have enabled significant improvements in efficiency, flexibility, and robustness. Malaji [6] reviewed a wide range of materials and concluded that both material properties and structural design critically influence EH performance.

Piezoelectric harvesters commonly use materials such as lead zirconate titanate (PZT) and polyvinylidene fluoride (PVDF). PZT offers high energy density but is brittle, whereas PVDF provides flexibility at the expense of lower conversion efficiency [22]. Thermoelectric devices rely on semiconductors with high Seebeck coefficients, such as bismuth telluride, while RF harvesters require antenna materials that balance conductivity, cost, and manufacturability.

Andrade [9] and Isioto et al. [23] further highlighted that material selection affects not only electrical performance but also environmental resilience. Harvesters deployed in harsh environments require corrosion-resistant and temperature-stable materials, while wearable and biomedical applications prioritize biocompatibility and mechanical flexibility.

The incorporation of nanomaterials, composites, and multifunctional structures continues to expand the potential of EH technologies. Ongoing research explores graphene-based electrodes, flexible polymers, and hybrid materials capable of achieving higher efficiency while maintaining long-term durability [22]. Ultimately, material selection bridges the gap between theoretical harvesting potential and practical deployment.

III. THE ROLE OF ENERGY HARVESTING IN COMBATING CLIMATE CHANGE

Beyond powering individual devices, energy harvesting (EH) technologies contribute to broader sustainability objectives, particularly in mitigating climate change. By leveraging renewable, ambient energy sources, EH reduces reliance on fossil fuels and lowers greenhouse gas emissions [1]–[3]. Several factors highlight this contribution:

Hhh

- *Utilization of Renewable Energy Sources:* EH systems exploit abundant and environmentally friendly energy sources, including solar radiation, wind, vibrations, and kinetic motion. Unlike fossil fuels, these sources do not produce carbon dioxide during operation [1].

- *Reduction in Overall Energy Consumption:* Low-power devices equipped with EH require less energy than conventional battery-powered systems. By decreasing demand from centralized electricity grids, EH indirectly reduces associated carbon emissions [25].

- *Extension of Device Lifetime:* By minimizing or eliminating battery replacements, EH reduces the environmental impact of battery production, transportation, and disposal. This is particularly significant given the hazardous materials in batteries, which contribute to pollution and greenhouse gas emissions [1], [25].

- *Support for Remote and Off-Grid Applications:* EH enables self-powered sensors for environmental monitoring, wildlife tracking, and climate assessment without dependence on external power infrastructure [8], [7]. These applications reduce carbon emissions while generating critical data for climate adaptation and mitigation strategies.

- *Minimization of Infrastructure Requirements:* EH-powered wireless sensor networks reduce the need for extensive cabling and grid connections, lowering the environmental footprint associated with constructing and maintaining power distribution systems [14].

- *Enablement of Smart and IoT Systems:* EH supports IoT-enabled buildings, transportation networks, and industrial processes by providing real-time energy monitoring and optimization. This reduces waste, improves operational efficiency, and indirectly lowers greenhouse gas emissions [11], [13].

Despite these advantages, EH technologies face challenges in efficiency, scalability, and cost. Most systems generate small amounts of power and require advanced materials and optimized circuits for effective operation. However, as material science advances and hybrid EH systems mature, EH is poised to play an increasingly significant role in global sustainability efforts. Its ability to harness abundant renewable energy at the micro-scale positions it as a key enabler of climate-conscious technological development.

IV. DISCUSSION

The review of energy harvesting (EH) technologies for low-power devices highlights both the opportunities and limitations that shape their current and future applications. This discussion synthesizes the findings from previous sections and evaluates EH in terms of efficiency, reliability, material considerations, and its broader contribution to sustainability.

COMPARATIVE PERFORMANCE OF TECHNIQUES

The comparative summary in Table 1 illustrates that each EH technique is strongly dependent on the characteristics

Comparative Performance of Techniques

The comparative summary in Table 1 illustrates that each EH technique is strongly dependent on the characteristics of its energy source. Photovoltaic (PV) systems consistently deliver the highest and most stable power output in outdoor environments, which accounts for their widespread use in wireless sensor networks and IoT devices [13], [14]. However, their performance is constrained in indoor, shaded, or cloudy conditions. Mechanical energy harvesters, particularly piezoelectric and triboelectric devices, offer high power densities in vibration-rich industrial environments but are inherently intermittent when mechanical activity is absent [3], [14].

RF energy harvesters are advantageous in urban settings due to the ubiquity of electromagnetic signals; nevertheless, they suffer from low conversion efficiency and often require large or complex antenna designs [19], [29]. Human energy and bioenergy harvesting are emerging areas with substantial potential for wearable technology and environmental monitoring. Their output, typically in the microwatt to milliwatt range, necessitates hybridization or ultra-low-power electronics for practical deployment [12], [22].

4.2 Factors Influencing Efficiency

Transduction mechanisms determine the fundamental efficiency limits of EH systems. Piezoelectric devices, for example, can generate high voltages from minimal mechanical input but are constrained by the brittleness of materials such as lead zirconate titanate (PZT) [22]. Thermoelectric generators (TEGs) perform effectively under large temperature gradients but exhibit limited output when gradients are small [19]. Recent advances in flexible polymers, nanomaterials, and hybrid composites show promise in mitigating these limitations [6], [9].

Equally critical is power management. Without effective maximum power point tracking (MPPT), impedance matching, and energy-aware scheduling, a significant portion of harvested energy may be lost before reaching storage or the load [7], [11], [13]. This highlights that integrating EH devices with storage and management systems is as important as improving the harvesters themselves.

EMERGING ROLE OF HYBRID SYSTEMS

A clear trend in recent literature is the growing adoption of hybrid EH systems, which combine multiple energy sources or transduction mechanisms to enhance reliability and overcome the limitations of single-source systems [14], [34]. For instance, integrating solar and vibration harvesters allows continuous operation under varying environmental conditions. In biomedical applications, hybrid systems combining piezoelectric and electromagnetic mechanisms have been used to extend the operational lifetime of implantable devices [35].

Although hybridization introduces increased circuit complexity and integration challenges, it represents the most practical approach for achieving continuous, scalable power supply for next-generation low-power electronics.

CONTRIBUTION TO SUSTAINABILITY AND CLIMATE CHANGE MITIGATION

EH technologies also contribute to environmental sustainability. By reducing dependence on batteries, EH mitigates the environmental impact associated with battery production, transport, and disposal [4], [5]. Moreover, EH enables autonomous IoT and sensor networks that enhance energy efficiency in smart cities, industrial processes, and transportation systems, indirectly reducing greenhouse gas emissions [1], [3].

While the power output of individual EH devices remains modest, the deployment of millions of EH-enabled devices can cumulatively lower carbon footprints, particularly in sectors such as agriculture, environmental monitoring, and building automation [6], [12].

RESEARCH GAPS AND FUTURE DIRECTIONS

Despite notable progress, several challenges remain:

1. Limited Efficiency: Most EH systems cannot serve as standalone power sources, making hybridization and ultra-low-power electronics necessary.
2. Scale and Deployment: Many studies remain at the laboratory or simulation scale, with fewer field deployments assessing long-term reliability.
3. Material Integration: Novel materials face challenges in cost, scalability, and durability under real-world conditions.
4. Standardization: The lack of standardized performance benchmarks complicates direct comparisons between EH systems.

Addressing these gaps is essential for transitioning EH from a niche technology to a mainstream solution capable of supporting the Trillion Sensor Universe.

V. CONCLUSION

This paper presented a comprehensive review of energy harvesting (EH) techniques for low-power device applications, emphasizing comparative performance, influencing factors, and environmental contributions. The analysis demonstrated that photovoltaic harvesting remains the most mature and widely deployed technique due to its high and stable power output. However, its dependence on light availability limits reliability in indoor, shaded, or cloudy environments. Mechanical and thermal harvesters are well-suited for vibration- and heat-rich environments, whereas RF and bioenergy-based approaches cater to specialized applications, including wearable devices and environmental monitoring. Human energy harvesting, despite low output, offers unique opportunities for biomedical and implantable systems.

The study further highlighted that the efficiency and reliability of EH systems are strongly governed by the choice of transduction mechanism, the effectiveness of power management strategies, and the properties of materials employed. Hybrid EH systems have emerged as a promising strategy to mitigate the limitations of individual techniques, providing more consistent and scalable power for next-generation IoT devices and wireless sensor networks.

Beyond technical performance, EH technologies contribute significantly to sustainability by reducing dependence on conventional batteries, minimizing electronic waste, and enabling smart systems that optimize energy usage. Nevertheless, several challenges remain, including low overall efficiency, limited large-scale deployments, material durability constraints, and the absence of standardized evaluation frameworks.

Future research should focus on:

1. Developing hybrid EH systems optimized for specific applications and operational environments.
2. Advancing material technologies that achieve a balance between high conversion efficiency, flexibility, and long-term durability.
3. Establishing standardized performance metrics and testing frameworks to facilitate comparison across EH systems.

Addressing these research gaps will enable EH technologies to transition from niche experimental applications to a central role in sustainable, self-powered electronics, supporting both technological innovation and climate-conscious development.

REFERENCES

[1]. T. Sanislav, G. Dan Mois, S. Zeadally, and S. Corneliu Folea, “Energy Harvesting Techniques for Internet of Things (IoT),” Mar. 2021, Information Science Faculty.

[2]. I. ul Hassan, H. Bae, M. Abid, S. Rehman, S. Ali, and Y. Lee, "Internet of Things and Its Applications: A Comprehensive Survey," Sensors, vol. 22, no. 7, p. 2675, Apr. 2022.

[3]. M. A. Ibrahim, M. A. Islam, and A. M. Al-Amin, "Techniques for energy harvesting from vibrational and thermal sources," Sensors, vol. 20, no. 21, p. 6275, 2020.

[4]. Y. Akinaga, "Fundamentals of energy harvesting: mechanisms and available energy sources," Jpn. J. Appl. Phys., vol. 59, no. SI, p. SI0801, Mar. 2020.

[5]. J. Davidson and C. Mo, "Recent advances in energy harvesting technologies for wireless sensor nodes," Proc. SPIE, vol. 9195, pp. 9195–9207, 2014.

[6]. P. V. V. V Malaji, "Materials and structures for energy harvesting: An overview," Mater. Today Proc., vol. 62, pp. 2696–2701, Jan. 2022.

[7]. H. Elahi, K. Munir, S. Daud, M. Shafique, M. R. Haider, and N. Javaid, "Energy harvesting techniques from human-body for autonomous sensors in internet of things applications: A review," IEEE Sens. J., vol. 21, no. 8, pp. 9516–9537, Apr. 2021.

[8]. H. Elahi, M. Malik, S. Mumtaz, M. Ajmal, F. B. Hussain, and O. Chughtai, "Erh-aware ambient assisted living through energy harvesting: Trends and opportunities," Sensors, vol. 20, no. 22, p. 6396, Nov. 2020.

[9]. J. S. Andrade, "Energy harvesting for powering wireless sensor nodes: A review," Micromachines, vol. 13, no. 8, p. 1221, Aug. 2022.

[10]. X. Bai, H. Ouyang, J. Xiao, J. Zheng, and C. Y. Lu, "Hybrid energy harvesting from mechanical and thermal energies for powering wireless sensor network nodes," J. Phys. Conf. Ser., vol. 1052, no. 1, p. 012007, Jul. 2018.

[11]. T. Sanislav, G. Dan Mois, S. Zeadally, and S. Corneliu Folea, “Energy Harvesting Techniques for Internet of Things (IoT),” Mar. 2021, Information Science Faculty.

[12]. I. ul Hassan, H. Bae, M. Abid, S. Rehman, S. Ali, and Y. Lee, "Internet of Things and Its Applications: A Comprehensive Survey," Sensors, vol. 22, no. 7, p. 2675, Apr. 2022.

[13]. M. A. Ibrahim, M. A. Islam, and A. M. Al-Amin, "Techniques for energy harvesting from vibrational and thermal sources," Sensors, vol. 20, no. 21, p. 6275, 2020.

[14]. M. Sanislav, M. V. Tam, G. Koley, C. Candolfi, E. Grossman, and T. Dumitru, "Wearable energy harvesting techniques applied to self-powered sensor systems and IoT devices," Appl. Sci., vol. 11, no. 17, p. 7871, Aug. 2021.

[15]. L. Liu, R. Zhu, J. Zhang, and B. Ren, "Enabling technologies of environmental energy harvesters for smart wireless sensors in subversive environments: A review," Sensors, vol. 21, no. 16, p. 5316, Aug. 2021.

[16]. S. S. Chitechi and F. O. Odoyo, "Power supply challenges in mobile devices: A need for alternative sources of energy," J. Comput. Eng. Informatics, vol. 4, no. 1, pp. 138–145, Mar. 2020.

[17]. A. Aldin, Y. Chen, and Q. Li, "Energy harvesting from radio frequency signals: Recent advances and future directions for Internet of Things," Nano Energy, vol. 104, p. 104621, Mar. 2023.

[18]. Y. Zhou, S. He, J. Wang, and Y. Gan, "Energy harvesting for human body motion: A review of modelling, mechanisms and strategy," Comput. Electr. Eng., vol. 88, p. 106832, Nov. 2020.

[19]. S. Sojan and G. Kulkarni, "A review on mechanical energy harvesting techniques," Int. J. Innov. Res. Sci. Eng. Technol., vol. 5, no. 5, pp. 8297–8305, May 2016.

[20]. I. E. Isioto, B. Abdul, S. Nouridinniavaran, N. Hasnan, and N. H. M. Hanif, "Energy harvesting techniques for microclimate monitoring systems deployment in harsh environments: A review," Renew. Sustain. Energy Rev., vol. 153, p. 111741, Jan. 2022.

[21]. K. Golabek and M. Strankowski, "Devices harvesting human-body energies for powering medical electronics: A review," Biosensors, vol. 14, no. 1, p. 48, Jan. 2024.

[22]. B. Pozo et al., "Harvested power and human body heat for powering e-textile UHF RFID sensor applications," IEEE J. Radio Freq. Ident., vol. 3, no. 4, pp. 220–227, Dec. 2019.

[23]. M. Isioto, B. Abdul, N. Nouriddin, H. Nouridin, M. Hanif, and M. N. Hanif, "Energy harvesting techniques for microclimate monitoring systems deployment in harsh environments: A review," Renew. Sustain. Energy Rev., vol. 153, p. 111741, 2022.

[24]. J. He, J. Xiao, T. Chen, T. Meng, J. Qiu, and Z. L. Wang, "Recent progress in TENG-based energy harvesting toward self-powered engineering systems," APL Mater., vol. 9, no. 9, p. 090902, Sep. 2021.

[25]. J. Davidson and C. Mo, "Recent advances in energy harvesting technologies for wireless sensor nodes," Proc. SPIE, vol. 9195, pp. 9195–9207, 2014

[26]. S. K. Karan, S. Majhi, S. Sonavane, D. Guha, and D. Ghose, "Powering sensor nodes using soil energy harvesting," Comput. Electron. Agric., vol. 172, p. 105350, May 2020.

[27]. Z. Wang, N. Wang, Z. Yang, F. Li, R. Zhang, and H. Li, "High-performance self-powered micro/nano-electromechanical systems in water motions for blue energy harvesting," IEEE/ASME Trans. Mechatronics, vol. 22, no. 4, pp. 1589–1597, Aug. 2017.

[28]. L. Zhao, L. Zheng, L. Tang, and Y. Wu, "Power extraction for a small-scale wave energy harvester from a coupled modeling perspective," Phys. Rev. E, vol. 103, no. 6, p. 063102, Jun. 2021.

[29]. N. V. Viet, M. Nishio, R. A. Rahim, and H. Kuwano, "Cell-competent self-powered ocean energy harvesting wave-driven system," IEEE J. Ocean. Eng., vol. 42, no. 1, pp. 189–198, Jan. 2017.

[30]. M. Pinuela, P. D. Mitcheson, and S. Lucyszyn, "Ambient RF energy harvesting in urban and semi-urban environments," IEEE Trans. Microw. Theory Tech., vol. 61, no. 7, pp. 2715–2726, Jul. 2013.

[31]. X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless networks with RF energy harvesting: A contemporary survey," IEEE Commun. Surv. Tutor., vol. 17, no. 2, pp. 757–789, 2015.

[32]. R. Lai, V. John, and J. Walker, "A review of methods for increasing output power in photovoltaic systems of vehicular applications," Int. J. Energy Res., vol. 44, no. 3, pp. 1524–1545, Mar. 2020.

[33]. N. Sheikholeslami, K. N. Rasi, H. M. Abouhenidi, and A. Morshedi, "A review on indoor photovoltaic energy harvesting for IoT sensor nodes," Wirel. Sens. Netw., vol. 13, no. 5, pp. 109–132, May 2021.

[34]. B. Waterbury and S. W. Wright, "Design of an electromagnetic energy harvester," in Energy Harvesting Technologies, Springer, 2013, pp. 203–215.

[35]. X. Bai, H. Ouyang, J. Xiao, J. Zheng, and C. Y. Lu, "Hybrid energy harvesting from mechanical and thermal energies for powering wireless sensor network nodes," J. Phys. Conf. Ser., vol. 1052, no. 1, p. 012007, Jul. 2018.

[36]. V. Demir, M. Ünlü, B. G. Akınoğlu, and B. G. Akınoğlu, "A review on micro energy harvesters for biomedical applications," Sens. Transducers, vol. 221, no. 3, pp. 9–17, 2018.

[37]. S. Niu, X. Wang, F. Yi, Y. S. Zhou, and Z. L. Wang, "A universal self-charging system driven by random biomechanical energy for sustainable operation of mobile electronics," Nat. Commun., vol. 6, no. 1, pp. 1–8, Sep. 2015.