Abstract:

This review paper provides a comprehensive analysis of various methods employed for acoustic energy harvesting (AEH), focusing on their efficiency and potential applications, particularly within the Internet of Things (IoT) landscape. By examining previous research on techniques such as Helmholtz resonators, quarter-wavelength resonators, acoustic metamaterials, and piezoelectric systems, we compare their energy outputs and highlight advancements in technology. The findings demonstrate that while methods like acoustic metamaterials and triboelectric energy harvesting show high efficiencies, integrating multiple approaches can further enhance performance. This review underscores the significance of AEH in powering IoT devices, paving the way for sustainable energy solutions in smart environments. Different parameters were then compared via plots.

Introduction:

In recent years, energy harvesting has emerged as a significant area of interest among researchers, scientists, and engineers, as it promises sustainable alternatives to conventional power sources [2][7]. The process of capturing ambient energy and converting it into usable electricity has led to the development of technologies like solar, wind, and geothermal energy harvesting, which are now commercially mature [2]. Among these, acoustic energy harvesting (AEH) is gaining attention as an unconventional method of tapping into environmental sound energy, converting what is often considered waste noise into a renewable power source [1][2].

Acoustic energy harvesting leverages mechanical sound waves, which are prevalent in daily life from sources like vehicles, airplanes, and industrial machinery, to generate electrical power [1][2]. Although AEH faces challenges due to the inherently low energy density of sound waves, which limits its application to high-noise environments, its advantages for powering low-consumption devices make it a promising area of study [2][7]. One of the main drawbacks is that the power generated by AEH systems cannot meet the demands of high-power applications, but its utility in low-power devices, such as those used in the Internet of Things (IoT), is becoming increasingly important [1][2].

The importance of AEH becomes evident in the context of IoT, where billions of smart devices require efficient, sustainable power sources. Traditional batteries, which are widely used in IoT devices, present limitations such as limited operational life and environmental concerns, especially in remote or inaccessible areas [4][5]. AEH, by converting ambient sound energy into electricity, offers a low-cost, low-impact solution to powering wireless sensor nodes (WSNs) in IoT networks [3][4][5]. Since IoT devices often have low power requirements, AEH aligns well with the energy needs of these technologies, providing a clean and sustainable alternative to conventional batteries [5][7].

At the core of AEH is the use of acoustic transducers, which convert sound waves into electrical energy via piezoelectric, electromagnetic, or triboelectric mechanisms [1][6]. Piezoelectric transducers, in particular, have shown great potential in converting mechanical vibrations from sound into usable electrical energy [6]. After conversion, power-managing circuits are used to regulate and store the harvested energy, making it available for IoT devices and other applications [1][3]. While AEH technology is still in development and faces efficiency challenges, its ability to offer green, sustainable energy solutions in the rapidly expanding IoT sector makes it an area of growing interest in modern energy harvesting research [3][4][7].

Methods for Acoustic Energy Harvesting:

Acoustic Energy Harvesting (AEH) is an innovative method that transforms sound waves into usable electrical energy. With the increasing demand for sustainable power sources, AEH offers a promising solution, especially in environments where sound is abundant. Various techniques have been developed to efficiently capture and convert acoustic energy, each with unique mechanisms tailored to specific applications. These methods pave the way for harnessing sound energy for low-power devices, especially in the growing field of the Internet of Things (IoT):

- **Helmholtz Resonator-Based Approaches:**
  Helmholtz resonators have been a focal point for acoustic energy harvesting (AEH), especially at the microscale, like in MEMS (Micro-Electro-Mechanical Systems) applications. One approach utilized a PVDF (Polyvinylidene Fluoride) cantilever inside the resonator's cavity, though the harvested power was only 0.1 μW due to the low piezoelectric coefficient of PVDF and weak internal sound-pressure distribution [1]. Hybrid AEH devices, combining piezoelectric and electromagnetic methods, showed better performance, generating 49 μW from the piezoelectric part and 3.16 μW from the electromagnetic part at 130 dB [1]. Innovations such as conical resonators and dual-structure resonators have been developed to enhance acoustical-mechanical coupling (interaction between sound waves and mechanical components), improving efficiency significantly [1].

  For low-frequency applications, a planar Helmholtz resonator featuring a coiled neck was proposed, capable of producing 27.2 μW at 217 Hz and 100 dB sound pressure level (SPL) [1]. The concept was extended to multifunctional designs, such as noise barriers that simultaneously offer sound insulation and energy harvesting [1]. Another promising approach involved an Electromechanical Helmholtz Resonator (EMHR), which converted acoustic energy into electrical energy through a piezoelectric diaphragm, achieving up to 30 mW of power output at 160 dB [7].

- **Piezoelectric Conversion:**
  Piezoelectric conversion utilizes materials that can transform mechanical strain energy into electrical energy through the piezoelectric effect. Common piezoelectric materials include polyvinylidene difluoride (PVDF), lead zirconate titanate (PZT), and barium titanate. Single-crystal piezoelectric materials have gained research interest due to their higher electromechanical coupling, significantly enhancing energy harvesting performance compared to conventional PZT-5A and PZT-5H materials [1]. Additionally, highly oriented PZT films exhibit a strong piezoelectric effect, generating sufficient strain under low-frequency conditions, although further investigation is necessary to optimize their application in acoustic energy harvesting (AEH) [1].

An acoustic energy harvester typically comprises three components: a resonator that oscillates at its resonant frequency to produce mechanical oscillations (sound), a membrane connected to the piezoelectric material, and a storage device. The piezoelectric material converts the vibrations induced by sound into electrical energy, which is then stored [2]. While many sound energy harvesters focus on piezoelectric effect-based nanogenerators, they often face low output performance due to the mismatch between the device's inherent frequency and common sound frequencies [3]. Piezoelectric energy harvesting (PEH) captures motion, vibration, and acoustic energy, and its significance is growing in the context of the Internet of Things (IoT) as alternative energy sources [4]. The concept of piezoelectricity was established by J. Curie and P. Curie in 1880, illustrating the two-way conversion between electrical and mechanical energies [5]. In practice, piezoelectric transducers are employed to capture sound waves and convert them into alternating current (AC) voltage signals [6].

- **Electromagnetic Conversion:**
  Electromagnetic conversion generates electrical energy through Faraday's law of electromagnetic induction. When a permanent magnet moves relative to a coil, an electrical potential is induced at the coil's terminals, with voltage depending on the rate of change in magnetic flux density and the coil's turns [1].

  Neodymium iron boron (NdFeB) is commonly used as a magnetic material due to its strong properties [1]. This combination enhances the efficiency of energy harvesting, especially in low-frequency environments where sound energy is prevalent.

- **Triboelectric Energy Harvesting:**
  Triboelectric energy harvesting utilizes triboelectric nanogenerators (TENGs) to convert mechanical energy into electrical energy. A TENG can be placed on a Helmholtz resonator, which enhances excitation at its resonant frequency, leading to increased voltage through the generation of triboelectric charges [1]. In another approach, TENGs made with flat organic films can effectively harvest acoustic energy, achieving a power output of 60.2 mW/m^2 and a maximal current density of 1.6 mA/m^2 [2].

  TENGs are increasingly relevant for applications in the Internet of Things (IoT) and portable self-power generators, meeting the growing demand for sustainable energy resources. These devices leverage both electrostatic induction and triboelectrification, exploring various friction generation modes and materials to optimize performance and broaden application possibilities [3].

- **Quarter-Wavelength Resonator-Based Approaches:**
  Quarter-wavelength resonators have been effectively utilized for acoustic energy harvesting (AEH) by integrating multiple polyvinylidene fluoride (PVDF) beams within a resonator tube. Research indicated that positioning the beam at the inlet maximized power output, while a zigzag beam arrangement outperformed aligned configurations. Replacing PVDF beams with lead zirconate titanate (PZT) beams further enhanced AEH performance significantly [1].

Additionally, a self-powered synchronized switch harvesting on inductor (SSHI) circuit was developed and integrated into a quarter-wavelength resonator-based AEH device. This configuration demonstrated optimal performance, achieving a harvested power of 0.796 mW under 112 dB sound pressure level (SPL) excitation at 196 Hz, showcasing the potential of such systems for efficient energy harvesting [2].

- **Acoustic Metamaterial-Based Approaches:**
  Acoustic metamaterials have gained significant attention as effective structures for enhancing acoustic energy harvesting (AEH) through mechanisms such as sound pressure focusing and amplification. For example, sonic crystals featuring point defects have been employed to confine acoustic energy, which facilitates the conversion of this energy into electrical power using polyvinylidene fluoride (PVDF) patches. An advanced prototype that incorporates a delicate electromechanical Helmholtz resonator (EMHR) has shown impressive performance improvements, with power outputs up to 23 times higher than conventional resonators. The research indicates that optimizing the configuration of PVDF beams within a quarter-wavelength resonator can maximize energy conversion efficiency, emphasizing the importance of structural design in achieving effective energy harvesting [1, 2].

  Moreover, innovative strategies such as the development of planar acoustic metamaterials and subwavelength defect structures have further enhanced energy harvesting capabilities. For instance, a double coiled-up acoustic cavity has been designed, incorporating a piezoelectric bimorph to significantly boost sound pressure and facilitate energy conversion. Other structures, such as a broadband AEH metasurface composed of coupled Helmholtz resonators and a piezoelectric (PZT) wafer, have achieved maximum power outputs of 90 mW at high sound pressure levels. These advancements demonstrate the potential of acoustic metamaterials not only for efficient energy harvesting but also for simultaneous noise insulation, paving the way for compact, multifunctional energy-harvesting devices that can operate effectively in low-frequency environments [3, 4].

- **Thermoacoustic Energy Harvesting:**
  Thermoacoustic energy harvesting (TAEH) is an innovative technology that leverages thermoacoustic engines to convert thermal energy into acoustic oscillations, which can then be transformed into electrical energy. This process occurs within a resonator tube containing a porous material situated between two heat exchangers. The heat exchangers create a temperature gradient that induces self-sustained acoustic oscillations, which can be harnessed using electroacoustic transducers, such as linear alternators or piezoelectric diaphragms. The advantages of TAEH include its simple design, low maintenance costs, long operational life, and the ability to utilize low-grade heat sources. Additionally, its environmentally friendly nature is enhanced by the use of non-toxic gases like air, helium, and nitrogen as the working media. However, practical challenges remain in achieving the desired efficiency levels in thermoacoustic systems .[2]

Research into TAEH includes the development of a simplified mathematical model of a thermoacoustic-piezoelectric (TAP) energy harvester, which integrates a standing wave thermoacoustic engine with a piezoelectric element. The analysis indicates that the frequency of self-excited oscillations is influenced by the natural frequency of the piezoelectric element rather than the electrical load. Maximum acoustic energy transfer occurs when the resonator's frequency aligns with that of the piezoelectric element. Furthermore, the power conversion efficiency improves significantly with higher load resistances, achieving efficiencies between 10% to 15% for certain configurations. This research emphasizes the importance of optimizing the resonator length and thermal properties to enhance the overall performance of thermoacoustic energy harvesters .[2]

Efficiency Comparisons:

Now, to compare the efficiencies of various Acoustic Energy Harvesting (AEH) methods, including Helmholtz resonators, quarter-wavelength resonators, acoustic metamaterials, piezoelectric, triboelectric, and thermoacoustic technologies. By evaluating the power output under different acoustic conditions, the aim is to highlight the strengths and limitations of each technique, providing insights into their potential applications in energy harvesting for IoT and other systems:

Energy Harvesting Approach	Harvested Power
Helmholtz Resonator-Based Approaches	0.1 (PVDF cantilever, 100 dB) [1]
	1.43 mW (100 dB, 170–206 Hz) [1]
	27.2 µW (100 dB, 217 Hz) [1]
	0.38 µW (PVDF in noise barrier, 100 dB) [1]
	30 mW (160 dB, Electromechanical HR) [2]
	42.2 µW (Airflow harvester, 20 m/s) [2]
	3.49 µW (Tunable HR, matched frequencies) [2]
Quarter-Wavelength Resonator-Based Approaches	0.796 mW (S-SSHI circuit, 112 dB, 196 Hz) [1]
Acoustic Metamaterial-Based Approaches	18 µW (Defect structure, 100 dB, 520 Hz) [1]
	7.3 µW (Helix metamaterial, 100 dB, 175 Hz) [1]
	200 µW (Piezoelectric patch, 114 dB, 155 Hz) [1]
	2 mW (MetaWall, 460 Hz) [1]
	90 mW (Broadband metasurface, 160 dB, 620 Hz) [1]
Piezoelectric Energy Harvesting	0.19 µW (118 dB, 850 Hz) [2]
	33.133 dBuW (96 dB) [3]
	2.5 µW (Raindrop impact, single unit) [4]
Triboelectric Energy Harvesting	60.2 mW/m² (TENG from vibrations) [3]
Thermoacoustic Energy Harvesting	10-15% efficiency (1000 Ω, tube length 0.5–5 cm) [2]
Electromagnetic Conversion	1.5–1.96 mW (143–470 Hz) [5]

Table 1: Raw comparison of Power Generated by different AEH methods.

In conclusion, the analysis of various energy harvesting approaches highlights significant differences in their performance. Helmholtz resonators demonstrate versatility with power outputs ranging from 0.1 µW to a peak of 30 mW under high sound pressure levels. The quarter-wavelength resonator shows potential but only achieves a maximum of 0.796 mW. In contrast, acoustic metamaterials reveal substantial capabilities, particularly with a 90 mW output from a broadband metasurface, indicating a promising avenue for future research. The triboelectric method also stands out with an impressive 60.2 mW/m² in vibration harvesting. While several methods show promise, further research is needed to optimize these technologies for real-world applications, especially in sustainable energy solutions for the expanding IoT landscape. Combining methods, such as integrating Helmholtz resonators with piezoelectric materials, could enhance the efficiency of acoustic energy harvesting devices.

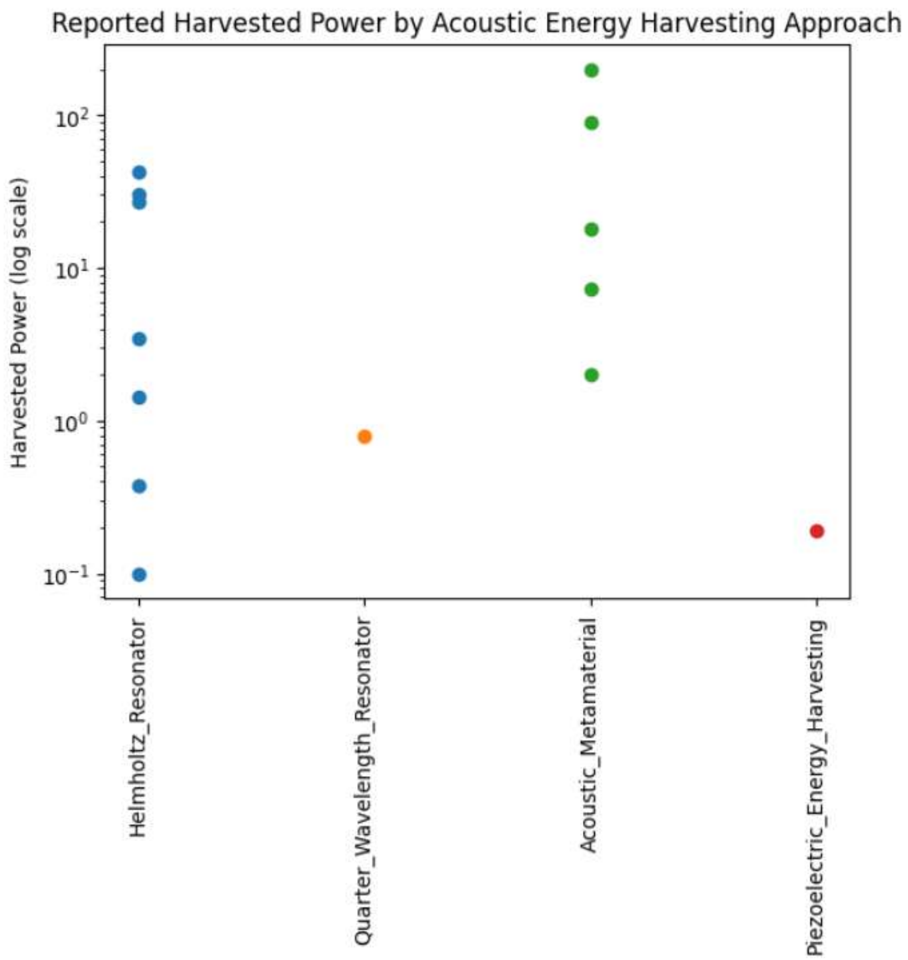

Figure 1: Harvested power values from literature for different acoustic energy harvesting approaches, plotted on a logarithmic scale

Reported harvested power spans ~3 orders of magnitude across approaches, even under broadly similar acoustic excitation levels.

- Helmholtz resonator approaches range roughly from sub-µW to tens of mW
- Acoustic metamaterials show higher upper bounds, reaching 10^1–10^2 mW
- Quarter-wavelength resonator data is sparse (single reported point)
- Piezoelectric-only approaches here appear lower, but this is underrepresented data

Observed differences in harvested power are strongly influenced by reporting density and experimental conditions rather than approach alone.

The highest reported values correspond to highly optimized and often extreme excitation conditions, limiting direct applicability to ambient acoustic environments.

The reported harvested power values show a wide spread across acoustic energy harvesting approaches, spanning multiple orders of magnitude. Helmholtz resonator-based systems exhibit the largest number of reported data points, reflecting their extensive investigation in the literature, with harvested power ranging from sub-microwatt to milliwatt levels. Acoustic metamaterial-based approaches demonstrate higher upper-bound power outputs; however, these values are often achieved under highly specific and optimized conditions, such as elevated sound pressure levels or narrowband resonance matching. In contrast, quarter-wavelength resonator and standalone piezoelectric approaches are represented by limited data, preventing robust comparative conclusions. Overall, the observed variability highlights the strong dependence of harvested power on experimental configuration rather than harvesting mechanism alone.

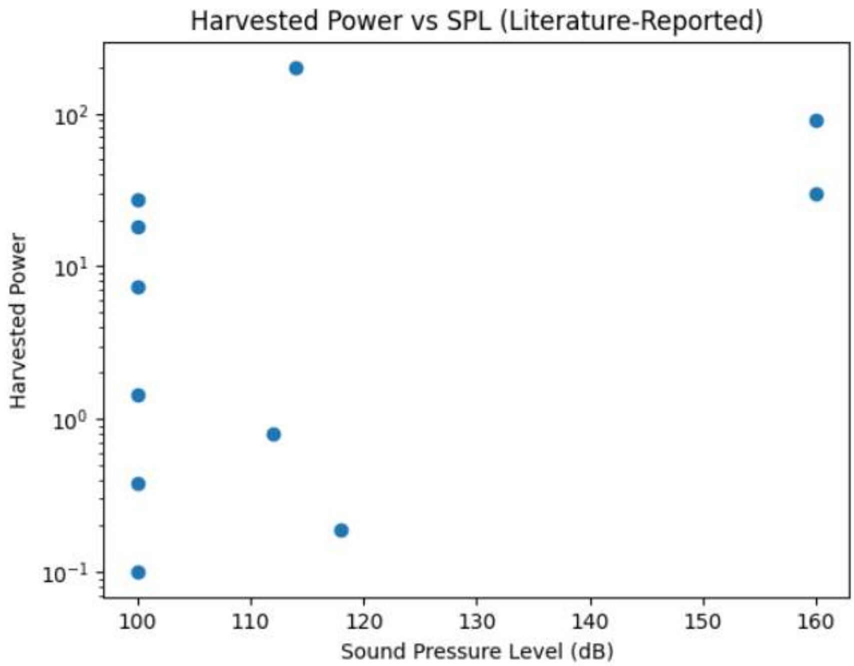

Figure 2: Literature-reported harvested power as a function of sound pressure level (SPL).

Although higher sound pressure levels generally enable higher harvested power, SPL alone does not determine energy output.

A weak positive trend with SPL is visible, but harvested power exhibits strong dispersion, indicating dominant dependence on harvester architecture, resonance tuning, and transduction mechanism.

The wide spread at fixed SPL highlights the challenge of cross-study comparison in acoustic energy harvesting literature.

The relationship between sound pressure level and harvested power shows a broad dispersion rather than a clear functional dependence. While the highest harvested power values are reported at elevated SPLs (~160 dB), significant variability exists even at comparable SPLs, with reported outputs spanning several orders of magnitude. This suggests that SPL alone is insufficient to predict harvesting performance, and that device architecture, resonance tuning, and transduction efficiency play a dominant role. The observed scatter underscores the difficulty of direct cross-study comparison and highlights the need for standardized reporting metrics in acoustic energy harvesting research.

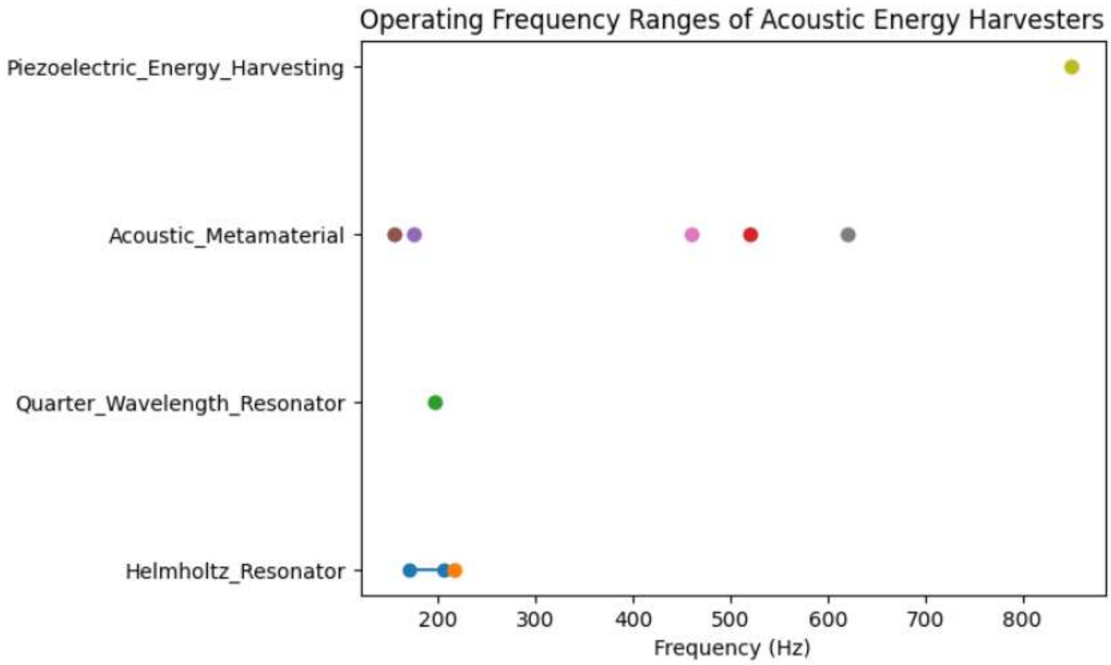

Figure 3: Operating frequency ranges of different acoustic energy harvesting approaches reported in the literature.

Resonator-based harvesting approaches exhibit strong frequency selectivity, operating efficiently only within narrow low-frequency bands.

Acoustic metamaterial-based harvesters demonstrate broader operational bandwidths compared to classical resonator designs, suggesting improved adaptability to variable acoustic environments.

Pure piezoelectric harvesting approaches are typically reported at higher operating frequencies, reflecting challenges in efficient low-frequency acoustic coupling.

The choice of harvesting architecture is strongly constrained by the dominant frequency content of the target acoustic environment.

The reported operating frequencies of acoustic energy harvesters show a clear dependence on the underlying harvesting architecture. Helmholtz and quarter-wavelength resonators operate predominantly in low-frequency bands (≈150–250 Hz), reflecting their reliance on geometrically tuned acoustic resonances. In contrast, acoustic metamaterial-based harvesters span a broader frequency range, extending into mid-frequency regimes, likely due to the presence of multiple resonant modes. Standalone piezoelectric harvesting approaches are primarily reported at higher frequencies, highlighting challenges in low-frequency acoustic coupling. These observations suggest that acoustic energy harvesting strategies must be selected based on the dominant frequency characteristics of the target sound environment.

Applications of Sound Energy Harvesting:

Acoustic Energy Harvesting (AEH) presents a promising approach to harnessing ambient sound energy, offering sustainable solutions for powering a variety of devices. As the demand for efficient energy sources grows, particularly in the Internet of Things (IoT) domain, AEH has gained significant attention. Its ability to convert sound into electrical energy not only enhances the functionality of low-powered devices but also addresses the limitations of traditional battery systems. Below are key applications of AEH, particularly its relevance in IoT:

- **Sustainable Energy Source:**
  Acoustic Energy Harvesting (AEH) utilizes the abundantly available sound energy in the environment, making it a sustainable option for powering various devices. This widespread availability allows AEH to serve as a reliable energy source that can be harnessed without significant ecological impact [3].
- **Powering Nano- and Microsensors:**
  AEH facilitates the conversion of sound energy into electrical energy, which is crucial for the operation of nano- and microsensors. These sensors play a vital role in applications such as environmental monitoring and structural health assessments, requiring a constant energy supply to function effectively [3].
- **Significant Impact on IoT Applications:**
  AEH is particularly advantageous for low-powered electronic devices, significantly enhancing the efficiency and reliability of Internet of Things (IoT) systems [4]. By powering autonomous wireless sensor networks (WSNs), AEH enables a wide range of critical IoT applications. For instance, it supports **industrial equipment monitoring**, **environmental condition tracking**, and **traffic management**. These applications rely on continuous energy supply, which AEH provides, ensuring operational continuity and improving overall system performance [8].
- **Addressing Battery Limitations:**
  Traditional battery systems for WSNs face limitations regarding duration and size, often necessitating frequent replacements and posing logistical challenges. In contrast, AEH offers a continuous energy supply that allows for the long-term deployment of devices in remote and hazardous locations. This capability is crucial for maintaining the functionality of IoT systems in environments where conventional energy sources are scarce [8].
- **Self-Powered Solutions:**
  In sectors like railways, AEH holds great potential for powering health monitoring sensors, signaling systems, and safety equipment. This is particularly important in areas where implementing conventional energy sources is difficult or impractical, as AEH can provide self-powered solutions that ensure operational continuity even in challenging environments [9].

Conclusion:

This review provides a comprehensive analysis of various methods for acoustic energy harvesting (AEH), highlighting their successes and challenges. By examining different techniques such as Helmholtz resonators, quarter-wavelength resonators, acoustic metamaterials, piezoelectric systems, and triboelectric harvesting, the paper illustrates the diversity of AEH technologies available. Many of these methods have demonstrated promising power outputs under specific conditions, but they also face significant challenges. Issues like scaling these technologies for larger applications, integrating them into existing systems, and optimizing their performance in different sound environments still need to be addressed. More research is essential to enhance these methods, improve their efficiency, and develop innovative solutions that cater to various applications. As the demand for energy from emerging technologies continues to grow, it becomes crucial to innovate in the field of AEH. Researchers should explore the combination of different approaches and the use of advanced materials to unlock the full potential of sound energy harvesting.

Furthermore, this paper emphasizes the importance of AEH in the context of the rapidly expanding Internet of Things (IoT) market. As IoT devices become more widespread, there is an increasing need for sustainable and self-sufficient power sources to support their operation. AEH can effectively meet this need by harnessing energy from ambient sound, providing an environmentally friendly alternative to conventional power sources. By integrating AEH into IoT applications, we can create more sustainable devices that function without depending solely on traditional energy systems. This review underscores the potential benefits of AEH in facilitating the growth of IoT and highlights the importance of continued exploration and research in this technology. By addressing the existing challenges and maximizing the advantages of AEH, we can pave the way for a greener and more energy-efficient future.

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