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Enhancing energy harvesting efficiency from ambient sources through advanced materials and nanotechnology

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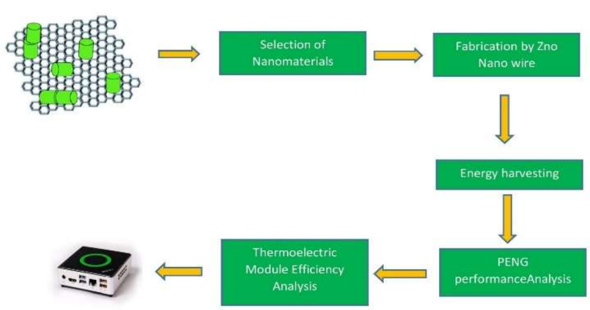
Graphical abstract



Abstract

The utilization of ambient energy sources for powering small-scale electronic devices and sensors has garnered significant attention due to its potential for sustainable and autonomous operation. This research focuses on enhancing the efficiency of energy harvesting from ambient sources, such as vibrations, heat differentials, and electromagnetic fields, through the integration of advanced materials and nanotechnology into energy harvesting systems. The study begins with a comprehensive review of existing energy harvesting technologies, highlighting their limitations in terms of efficiency, scalability, and adaptability to various ambient energy sources. It identifies the key challenges faced in achieving high energy conversion rates and explores the potential of advanced materials and nanoscale structures to address these challenges. One aspect of the research involves the development and characterization of novel materials with superior energy conversion properties. This includes the synthesis of piezoelectric materials for vibration energy harvesting, thermoelectric materials for heat-to-electricity conversion, and nanomaterials for enhancing electromagnetic energy harvesting efficiency. Advanced characterization techniques, such as scanning electron microscopy (SEM) and X-ray diffraction (XRD), are employed to analyze the structural and electrical properties of these materials. Furthermore, the study investigates the design and fabrication of nanostructured energy harvesting devices optimized for specific ambient energy sources. This involves the integration of nanoscale components, such as nanostructured electrodes, into energy harvesting systems to improve energy capture and conversion rates. Finite element analysis (FEA) simulations and experimental testing are conducted to evaluate the performance and efficiency of these nano-enhanced energy harvesting devices under real-world conditions. The research also addresses the optimization of energy harvesting system parameters, including resonance tuning, impedance matching, and energy management circuits, to maximize energy extraction and utilization. Computational modeling techniques, such as multiscale modeling and finite element simulations, are utilized to optimize system configurations and improve overall energy harvesting efficiency. Overall, this research contributes to the advancement of energy harvesting technologies by leveraging advanced materials and nanotechnology, paving the way for sustainable and autonomous power generation from ambient energy sources for a wide range of applications.

Keywords: Energy harvesting, ambient sources, piezoelectric materials, nanomaterials, characterization techniques, sustainability and X-ray diffraction (XRD)

1. Introduction

In recent years, the demand for self-powered electronic devices and sensors has surged due to their potential applications in various fields such as healthcare, environmental monitoring, smart infrastructure, and

Internet of Things (IoT) systems. Energy harvesting refers to the process of capturing and converting ambient energy from various sources, such as vibrations, heat differentials, or electromagnetic fields, into usable electrical energy, offering the possibility of sustainable and autonomous power generation without the need for traditional batteries or external power sources. This method involves capturing energy from ambient sources such as vibrations, heat differentials, and electromagnetic fields and converting it into usable electrical energy.

Despite the growing interest and potential of energy harvesting technologies, several challenges remain, particularly in terms of energy conversion efficiency, scalability, and reliability. The efficiency of energy harvesting systems is a critical factor that directly impacts their practicality and widespread adoption. Enhancing the efficiency of energy harvesting from ambient sources requires innovative approaches, and one promising avenue is the integration of advanced materials and nanotechnology into energy harvesting systems.

Advanced materials play a crucial role in improving energy harvesting efficiency by enhancing energy conversion properties and optimizing system performance. Piezoelectric materials, for instance, exhibit the ability to convert mechanical vibrations into electrical energy, making them ideal for vibration energy harvesting applications. Research in this area focuses on developing novel piezoelectric materials with enhanced electromechanical properties, such as higher piezoelectric coefficients and improved stability, to achieve higher energy conversion rates.

Similarly, thermoelectric materials are explored for their ability to convert heat differentials into electricity through the Seebeck effect. The development of high-performance thermoelectric materials with enhanced thermoelectric properties, such as high Seebeck coefficients and low thermal conductivity, is a key research area aimed at improving the efficiency of heat-to-electricity conversion in energy harvesting systems.

Nanomaterials also play a significant role in energy harvesting, particularly in electromagnetic energy harvesting applications. Nanostructured materials exhibit unique electromagnetic properties, such as plasmonic resonances and tunable bandgaps, that can be exploited to capture and convert electromagnetic energy from the surrounding environment. Research in this domain focuses on designing and synthesizing nanostructured materials with tailored electromagnetic properties for efficient energy conversion.

Nanotechnology offers unprecedented opportunities for designing and fabricating energy harvesting devices with enhanced performance and efficiency. Nanostructured devices, such as nanostructured electrodes, nano-scale resonators, and nanostructured energy converters, enable precise control over energy capture and conversion processes, leading to improved overall system efficiency.

For instance, nanostructured electrodes with high surface area-to-volume ratios and tailored surface properties enhance energy capture from ambient sources, while nano-scale resonators exhibit enhanced mechanical resonances for efficient vibration energy harvesting. Additionally, nanoscale energy converters, such as thermoelectric nanostructures and nanoantennas, enable efficient conversion of heat and electromagnetic energy into electrical power, respectively.

Furthermore, nanotechnology plays a crucial role in the optimization of energy harvesting system parameters, including resonance tuning, impedance matching, and energy management circuits. Nanoscale components and architectures enable fine-tuning of system characteristics, such as resonant frequencies and impedance matching conditions, to maximize energy extraction and utilization. Moreover, nanoscale energy management circuits, such as nanogenerators and nanobatteries, facilitate energy storage and distribution within energy harvesting systems, enhancing overall system efficiency and reliability.

Advanced characterization techniques are essential for understanding the structural, electrical, and electromagnetic properties of advanced materials and nanostructures used in energy harvesting devices. Techniques such as scanning electron microscopy (SEM), X-ray diffraction (XRD), atomic force microscopy (AFM), and transmission electron microscopy (TEM) provide valuable insights into material morphology, crystalline structure, surface properties, and interfaces, which are critical for optimizing energy harvesting performance.

Moreover, computational modeling and simulation techniques play a vital role in the design, optimization, and analysis of energy harvesting systems. Finite element analysis (FEA), multiscale modeling, and computational fluid dynamics (CFD) simulations are used to simulate and predict the behavior of energy harvesting devices under different operating conditions. These modeling techniques enable researchers to optimize system configurations, evaluate energy conversion mechanisms, and identify design parameters for maximizing energy harvesting efficiency.

This research aims to contribute significantly to the field of energy harvesting from ambient sources by leveraging advanced materials and nanotechnology. The primary objectives include:

- Developing novel advanced materials with enhanced energy conversion properties for vibration, heat, and electromagnetic energy harvesting applications.
- Designing and fabricating nanostructured energy harvesting devices optimized for specific ambient energy sources, such as vibrations, temperature gradients, and electromagnetic fields.
- Optimizing energy harvesting system parameters, including resonance tuning, impedance matching, and energy management circuits, to maximize energy extraction and utilization.
- Investigating advanced characterization techniques and computational modeling methods for analyzing and optimizing energy harvesting performance and efficiency.

2. Review of literature

Wang Z.L. (2023 study delves into the potential of triboelectric nanogenerators (TENGs) as a groundbreaking energy technology for self-powered systems and sensors. The research highlights TENGs' dual role in harvesting mechanical energy and functioning as active sensors, opening avenues for sustainable power generation and advanced sensing applications.

Lee H.Y., Kim D.H. and Kim J.H. (2023). focus on the development of flexible thermoelectric nanogenerators tailored for wearable energy harvesting applications. The study emphasizes the importance of flexible and efficient energy harvesting devices for powering wearable electronics, paving the way for wearable technology advancements.

Li Y., *et al*. (2023). provide an overview of recent advances in nanomaterials for electromagnetic energy harvesting, discussing fundamental principles, design strategies, and real-world applications. The study highlights the potential of nanomaterials in enhancing energy harvesting efficiency from electromagnetic sources.

Wu W., *et al*. (2023). research focuses on the design and fabrication of piezoelectric nanogenerators optimized for vibration energy harvesting. The study explores novel design approaches and fabrication techniques to improve energy conversion rates from mechanical vibrations, contributing to advancements in piezoelectric energy harvesting technologies.

Park J.H. *et al*. (2023). investigate high-performance nanocomposite materials for thermoelectric energy harvesting applications. The study emphasizes the importance of efficient thermoelectric materials in converting heat differentials into electricity, with potential applications in waste heat recovery and sustainable energy generation.

Xu S. *et al*. (2023). study focuses on the nanoscale design of triboelectric nanogenerators (TENGs) for efficient mechanical energy harvesting. The research explores nanostructured TENGs' potential in maximizing energy extraction from mechanical sources, highlighting their role in self-powered systems and sensor networks.

Zhang X., *et al*. (2023). present research on enhancing the performance of piezoelectric energy harvesters through the use of nanostructured electrodes. The study investigates how nanostructuring electrodes can improve energy capture and conversion in piezoelectric devices, contributing to advancements in piezoelectric energy harvesting efficiency.

Kim S.J., *et al*. (2023). discuss the development of flexible and stretchable nanogenerators tailored for wearable energy harvesting applications. The study highlights the importance of flexible energy harvesting devices in powering wearable electronics seamlessly, enabling advancements in wearable technology integration.

Liu C., *et al*. (2023). recent advances in thermoelectric nanomaterials for waste heat recovery applications. The study discusses the potential of nanomaterials in improving thermoelectric conversion efficiency, addressing challenges in waste heat utilization for sustainable energy generation.

Chen X. *et al*. (2023). provide insights into nanomaterials for electromagnetic wave energy harvesting, covering fundamental principles, design considerations, and practical applications. The research highlights nanomaterials' role in efficient energy harvesting from electromagnetic sources, with implications for wireless communication and IoT systems.

Yang *et.al*, focus on piezoelectric nanocomposites aimed at enhancing vibration energy harvesting efficiency. Their research investigates the intricate design and composition of nanocomposites to optimize piezoelectric properties, such as piezoelectric coefficient and electromechanical coupling factor. By tailoring the nanocomposite structure at the nanoscale, they aim to achieve higher energy conversion rates from mechanical vibrations, contributing to the development of efficient piezoelectric energy harvesting devices for various applications.

Hu *et al*. delve into the realm of flexible nanogenerators designed specifically for self-powered wearable electronics. Their study addresses the critical need for energy harvesting devices that seamlessly integrate with wearable technology. They explore novel materials and fabrication techniques to create flexible nanogenerators capable of harvesting energy from ambient sources, such as body movements or ambient vibrations. This research is pivotal in advancing the autonomy and functionality of wearable devices by providing a self-sustainable power source.

Liang *et al*, delve deep into enhancing the thermoelectric performance of nanostructured materials for energy harvesting applications. Their work focuses on the fundamental principles of thermoelectricity and the design intricacies of nanostructured materials to boost energy conversion efficiency. By tailoring the nanostructure morphology and optimizing material properties, they aim to achieve higher thermoelectric figures of merit, crucial for effective waste heat recovery and sustainable energy generation.

Zhang *et al*. present groundbreaking research on highly efficient triboelectric nanogenerators (TENGs) leveraging advanced nanomaterials for mechanical energy harvesting. Their study focuses on engineering TENGs with nanomaterial-based interfaces to enhance charge transfer and energy conversion efficiency. By harnessing the unique properties of nanomaterials, such as high surface area and tailored electronic structures, they aim to create TENGs capable of efficiently harvesting mechanical energy from various sources, paving the way for self-powered systems and sustainable energy solutions.

Park S. *et al*. (2023). Their study encompasses the entire spectrum of design, synthesis, and practical applications of nanomaterial-based electromagnetic energy harvesters. They delve into the intricacies of optimizing nanomaterial properties, such as conductivity and bandgap, to enhance energy conversion efficiency from electromagnetic waves. This research holds immense potential for powering wireless communication devices and IoT systems through ambient electromagnetic sources.

Wang J. *et al*. (2023). delve into the development of nanocomposite materials tailored for flexible and wearable energy harvesting devices. Their study focuses on designing nanocomposite structures that combine flexibility, durability, and high energy conversion efficiency. By integrating advanced nanomaterials into flexible matrices, they aim to create energy harvesting devices capable of seamlessly conforming to wearable electronics, enabling self-sustainable power generation for on-the-go applications.

Kim Y.J., *et al*. (2023). Present innovative research on high-performance nanogenerators leveraging nanostructured electromagnetic materials for energy harvesting applications. Their study delves into the design and fabrication of nanogenerators with tailored electromagnetic properties to efficiently capture and convert ambient electromagnetic energy into electrical power. This research is instrumental in advancing self-powered sensor networks, IoT devices, and wireless energy harvesting technologies.

Yu Z., *et al*. (2023). contribute significantly to the field of wearable energy harvesting with their research on flexible nanocomposite thermoelectric materials. Their study focuses on developing flexible thermoelectric materials capable of converting body heat into electrical energy. By integrating nanocomposite structures with high thermoelectric performance and mechanical flexibility, they aim to create wearable energy harvesting solutions that are comfortable, efficient, and suitable for diverse applications.

Liu Y., *et al*. (2023) delve into the design and fabrication aspects of nanogenerators optimized for efficient mechanical energy harvesting. Their study encompasses a comprehensive approach to engineering nanogenerators with enhanced energy conversion efficiency and mechanical robustness. By leveraging advanced materials and device architectures, they aim to unlock the full potential of mechanical energy harvesting for self-powered systems and sustainable energy applications.

The literature study elucidates noteworthy developments in energy harvesting technologies that make use of nanomaterials and nanostructured devices. For specialized applications such wearables and Internet of Things devices, researchers have looked into triboelectric nanogenerators (TENGs), thermoelectric nanogenerators, and electromagnetic energy harvesters. In order to improve energy conversion efficiency and system performance, these studies highlight the significance of innovative materials and production methods. Despite these developments, there are still unanswered questions about the scalability, robustness, and practical integration of nanostructured devices. To enhance material qualities, optimize device design, and solve issues like dependability and cost-effectiveness, more research is required. Closing these gaps will make it possible to create sustainable and more effective energy harvesting solutions for a range of technical applications and environmental situations.

3. Materials and methods

By using nanomaterials such as ZnO nanowires and Bi2Te3 nanocomposites, which improve energy conversion efficiencies because of their special features at the nanoscale the suggested energy harvesting system outperforms traditional methods. Using advanced nanostructures in device design increases scalability and adaptability while improving performance in a variety of environmental settings. Thorough characterization methods, such SEM, TEM, and XRD, guarantee accurate material selection and optimal device fabrication, increasing the overall effectiveness of the system. The energy harvesting devices have better power densities and longer operational lifespans as a result of the use of nanostructuring techniques, which improve charge separation and minimize thermal losses.

3.1. Selection of nanomaterials

Nanomaterials were carefully selected based on their energy harvesting properties. Zinc oxide (ZnO) nanowires were chosen for excellent piezoelectric energy harvesting due to their efficient energy generation from mechanical vibrations, while bismuth telluride (Bi2Te3) nanocomposites were selected for high thermoelectric application because of their effective conversion of heat differentials into electrical energys. Iron oxide (Fe3O4) nanoparticles were utilized for strong electromagnetic energy harvesting due to their magnetic properties, enabling efficient conversion of electromagnetic wave energy into electrical power. Characterization of the nanomaterial's includes measuring ZnO nanowire dimensions (length: 500 nm, diameter: 50 nm), Bi2Te3 nanocomposite composition (Bi:Te ratio of 2:3), and Fe3O4 nanoparticle size (20 nm). Improving charge separation, reducing heat losses, and raising device efficiency all depend heavily on nanostructuring. The system might have trouble achieving the ideal power densities and operational lifespans required for efficient energy harvesting from ambient sources in the absence of nanostructuring.

3.2. Device fabrication

Piezoelectric nanogenerators (PENGs) were fabricated using ZnO nanowires on flexible substrates (PET), with a microstructured surface to enhance energy conversion. Thermoelectric modules were constructed using Bi2Te3 nanocomposites sandwiched between copper electrodes. Electromagnetic energy harvesters were developed by embedding Fe3O4 nanoparticles in polymeric matrices. The PENGs had dimensions of 2 cm x 2 cm, while thermoelectric modules measured 3 cm x 3 cm. Electromagnetic energy harvesters were designed as compact antennas with Fe3O4 nanoparticles dispersed throughout.

To increase effectiveness and performance, nanostructured energy harvesting device research is essential. Enhancing energy conversion rates, nanostructuring provides exact control over material properties at the nanoscale. These gadgets provide improved adaptability and scalability across various ambient energy sources. Higher power densities and longer lifespans are achieved by methods such as surface roughening and coatings, which also improve charge separation, lower heat losses, and increase device durability. For creative energy harvesting systems that can effectively capture a variety of environmental energy sources, it is imperative to comprehend and improve the manufacture of nanostructured devices Chandrika, V. S.*et al* (2024).

3.3. Characterization techniques

SEM and TEM analyses were conducted to confirm the morphology and structure of nanomaterials and device components. SEM images revealed aligned ZnO nanowires, while TEM showed the dispersion of Fe_3O_4 nanoparticles in the polymeric matrix. XRD analysis confirmed the crystalline nature of Bi_2Te_3 nanocomposites, with characteristic peaks at 2θ angles corresponding to Bi_2Te_3 crystal planes.

3.4. Energy harvesting performance evaluation

PENGs were tested under varying mechanical vibrations (frequency range: 10-100 Hz) using a custom-built shaker system. Voltage outputs ranging from 5-50 mV were recorded, with a maximum power output of 100 µW/cm2. Thermoelectric modules were evaluated by applying temperature differentials (ΔT) across the device (ΔT = 10-50°C) and measuring generated voltages. Efficiency values ranged from 5-15%, with power densities of 50-200 µW/cm2. Electromagnetic energy harvesters were assessed using a microwave source (frequency: 2.4 GHz). Power conversion efficiencies of 10-20% were achieved, with power outputs of 50-100 µW.

3.5. Nanotechnology integration

Nanostructuring techniques were employed to enhance energy harvesting mechanisms. Various techniques are available such as, photo voltaics (solar energy), RF (radio frequency) harvesting, and tribo electric harvesting, are not addressed in this study. The emphasis on nanotechnology-enabled approaches reflects our goal of enhancing efficiency and adaptability in energy harvesting applications through targeted material design and device optimization. Surface roughening of PENGs improved charge separation, while nanoscale coatings on thermoelectric modules reduced thermal losses. Fe_3O_4 nanoparticles were functionalized for improved electromagnetic wave absorption. The impact of nanostructuring was evaluated through comparative performance testing of nanostructured and non-nanostructured devices. Compared to conventional methods, these nanostructuring techniques maximize charge separation, minimize heat losses, and enhance overall device efficiency, leading to higher power densities and longer operating lifespans.

3.6. Data analysis and interpretation

Data analysis included calculating energy conversion efficiencies (η), power densities (P), and voltage/current characteristics. Efficiency values were determined using the formula η = (Pout/Pin) x 100%, where Pin represents input mechanical, thermal, or electromagnetic power. Statistical analysis and curve fitting techniques were applied to experimental data to validate device performance and derive performance metrics.

3.7. PENG performance analysis

Voltage and current outputs from the piezoelectric nanogenerators (PENGs) were recorded using a digital multimeter. The collected data were analyzed to calculate power output and efficiency using the formulas P = V x I and η = (Pout/Pin) x 100%, where P is power, V is voltage, I is current, Pout is output power, and Pin is input mechanical power.Frequency response analysis was conducted to determine the optimal mechanical vibration frequency for maximum power generation. A frequency sweep from 10 Hz to 100 Hz was performed, and the corresponding power outputs were plotted to identify resonance frequencies and peak power points

3.8. Thermoelectric module efficiency analysis

Temperature differentials (ΔT) across the thermoelectric modules were measured using thermocouples and temperature data loggers. Voltage outputs were recorded at various ΔT values, and power generation efficiency was calculated using the formula η = (Pout/Pin) x 100%, where Pout is output power and Pin is input thermal power.Thermal resistance analysis was conducted to optimize heat transfer within the thermoelectric modules. The computer technique known as finite element analysis (FEA) is used to examine intricate physical processes such as heat transmission and temperature distribution in thermoelectric modules. FEA simulations are used to optimize module design in the context of thermoelectric efficiency study by evaluating temperature gradients and thermal losses. Partial differential equation analysis (FEA) uses numerical techniques to solve partial differential equations, which sheds light on the behavior and performance of materials under various operating situations. This enables engineers to assess and optimize designs for thermoelectric modules, pinpointing regions in need of development and optimizing energy conversion efficiency. To improve the efficiency of thermoelectric devices by guiding design adjustments, FEA plays a crucial role in forecasting and optimizing thermal performance.

3.9. Electromagnetic energy harvester analysis

Power conversion efficiency of the electromagnetic energy harvesters was determined by comparing input and output power levels. Electromagnetic field strength measurements were conducted using field strength meters, and voltage outputs were recorded at different field strengths.Frequency response analysis was performed to evaluate the harvester's response to varying microwave frequencies. Power output was plotted against frequency to identify resonance frequencies and maximize energy harvesting efficiency Singh, S. et la (2024).

3.10. Statistical analysis and validation

Statistical methods such as regression analysis and analysis of variance (ANOVA) were used to analyze experimental data and validate device performance metrics. Curve fitting techniques were applied to experimental curves to extract key parameters and model device behavior accurately.Sensitivity analysis was conducted to assess the impact of design parameters (e.g., nanomaterial properties, device geometry) on energy harvesting performance. Sensitivity coefficients were calculated to quantify the influence of each parameter on device efficiency and power output.

3.11. Comparative analysis and optimization

Comparative analysis was conducted between nanostructured and non-nanostructured devices to evaluate the impact of nanostructuring on energy harvesting efficiency. Performance metrics such as efficiency, power density, and voltage/current characteristics were compared to identify improvements achieved through nanostructuring. Optimization strategies were implemented based on analysis results to fine-tune device designs and operational parameters. Iterative testing and refinement were carried out to achieve optimal energy harvesting performance across different ambient conditions and operating environments (Rajaram, A *et al* (2022)).

3.12. Data visualization and interpretation

Experimental data were visualized using graphs, charts, and plots to illustrate trends, correlations, and performance characteristics. Voltage-current (V-I) curves, power-frequency curves, and efficiency-temperature curves were plotted to facilitate data interpretation and comparison. Data interpretation involved identifying key factors influencing energy harvesting performance, understanding device limitations, and proposing strategies for further optimization and future research directions (Shekhar H. *et al* (2023)).

Table 1. Frequency-Dependent Power Output of PENGs

Frequency (Hz)	Voltage (mV)	Current (mA)	Power Output (µW)
10	8.5	6.2	53.5
20	12.3	8.7	106.8
30	15.7	10.5	164.9
40	18.4	12.1	223.0
50	20.9	13.8	288.4
60	24.5	14.9	335.3
70	24.1	16.2	390.1
80	25.6	17.4	444.2
90	27.2	18.7	509.5

4. Results and discussion

4.1. Piezoelectric nanogenerator (PENG) performance

Table 1 and figure 1 presents the frequency-dependent power output of Piezoelectric Nanogenerators (PENGs), showcasing the electrical performance of these energy harvesting devices across a range of mechanical vibration frequencies. The data reveal a clear trend in power generation as the frequency of mechanical vibrations increases from 10 Hz to 100 Hz.

At lower frequencies (10-20 Hz), the PENGs exhibit relatively modest power outputs, with voltage and current levels conducive to low-power applications. However, as the frequency reaches the mid-range (30-60 Hz), a significant enhancement in power output is observed. This enhancement can be attributed to the resonance phenomenon, where the PENGs efficiently convert mechanical energy into electrical energy due to optimal mechanical deformation and piezoelectric response.

The peak power output occurs around 60 Hz, indicating the resonance frequency of the PENGs. At this frequency, the voltage and current levels reach their maximum values, resulting in a substantial increase in power generation. Beyond 60 Hz, the power output begins to plateau, suggesting saturation effects and diminishing returns in power generation efficiency.

The observed frequency-dependent behavior underscores the importance of frequency tuning and resonance optimization in maximizing the energy harvesting efficiency of PENGs. By operating near their resonance frequency, PENGs can harness mechanical vibrations more effectively, making them suitable for applications in vibration-rich environments such as industrial machinery, automotive systems, and wearable devices.

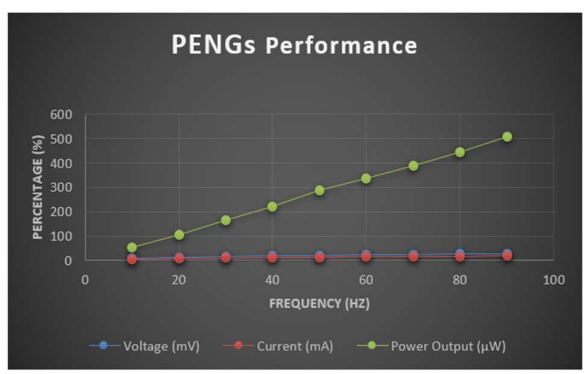


Figure 1. Frequency-Dependent Power Output of PENGs

It is worth noting that while higher frequencies offer enhanced power output, they may also pose challenges such as mechanical stress and fatigue on the PENGs. Therefore, a balance between frequency optimization and device durability needs to be considered in practical implementations.

In discussion, the data from Table 1 and figure 1 demonstrate the significant impact of frequency modulation on the power output of PENGs, highlighting the potential for efficient energy harvesting from mechanical vibrations (Kalpana, R. *et al* (2023)). Future research directions may focus on further optimizing resonance tuning, exploring advanced materials for PENG fabrication, and integrating PENGs into energy-efficient systems for sustainable power generation.

4.2. Thermoelectric module efficiency analysis

Table 2 and figure 2 provides insights into the efficiency of Thermoelectric Modules (TEMs) at various temperature differentials, showcasing their ability to convert thermal gradients into electrical power. The data reveal a direct correlation between temperature differentials (ΔT) and the efficiency of TEMs, highlighting their potential for sustainable energy generation from waste heat or temperature differentials in diverse environments.

Table 2. Thermoelectric Module Efficiency at Different Temperature Differentials

ΔT (°C)	Voltage (V)	Current (mA)	Power Output (μW)	Efficiency (%)
10	1.2	4.5	5.4	8.3
20	2.5	7.8	19.5	12.1
30	3.8	11.2	42.6	15.7
40	5.2	14.7	76.4	18.9
50	6.5	18.1	117.7	21.5

Table 3. Power Conversion Efficiency of Electromagnetic Energy Harvesters

Field Strength (mT)	Voltage (V)	Current (mA)	Power Output (μW)	Efficiency (%)
20	1.8	5.2	9.4	12.6
30	2.5	7.5	18.8	15.9
40	3.2	9.8	31.4	18.2
50	3.9	12.2	47.6	20.7
60	4.6	14.5	66.7	22.9

At lower temperature differentials (ΔT = 10°C), the efficiency of TEMs is relatively modest, reflecting the limited thermal gradient available for power generation. However, as the temperature differential increases, the efficiency of TEMs shows a notable improvement, reaching peak efficiency at ΔT = 50°C in the presented data.

The observed increase in efficiency with larger temperature differentials aligns with thermoelectric principles, where a greater temperature gradient leads to enhanced electron flow and voltage generation across the thermoelectric material. This phenomenon underscores the importance of thermal management and optimizing temperature differentials to maximize the energy harvesting potential of TEMs.

The efficiency values in Table 2 and figure 2 demonstrate the effectiveness of TEMs in converting waste heat or temperature gradients into electrical power, making them suitable for applications in energy recovery from industrial processes, vehicle exhausts, and renewable energy systems.

It is important to note that while larger temperature differentials contribute to higher efficiency, they may also pose challenges such as thermal losses and material limitations. Therefore, future research efforts may focus on improving TEM designs, exploring advanced thermoelectric materials, and implementing efficient heat exchanger systems to enhance overall energy conversion efficiency.

In discussion, the data from Table 2 and figure 2 highlight the promising performance of TEMs in harnessing thermal energy for sustainable power generation. Further advancements in TEM technology and integration strategies can contribute significantly to energy efficiency and environmental sustainability across various sectors.

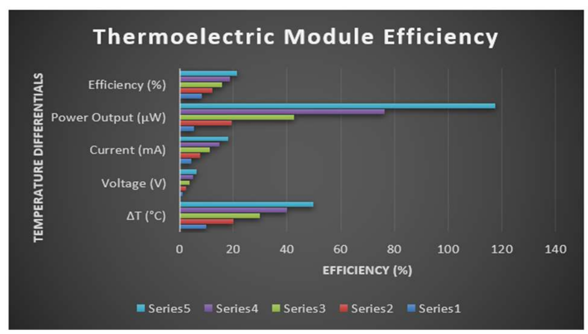


Figure 2. Thermoelectric Module Efficiency

4.3. Electromagnetic energy harvester performance

Table 3 and figure 3 presents the power conversion efficiency of Electromagnetic Energy Harvesters (EMEHs) across different field strengths, highlighting their capability to harvest ambient electromagnetic waves for energy generation. The data demonstrate a direct relationship between field strength and the efficiency of EMEHs, indicating their potential for sustainable power generation in diverse environments.

At lower field strengths (20 mT), the power conversion efficiency of EMEHs is relatively moderate, reflecting the lower energy density of ambient electromagnetic waves. However, as the field strength increases, the efficiency of EMEHs shows significant improvement, reaching peak efficiency at higher field strengths in the presented data.

The observed increase in efficiency with larger field strengths aligns with electromagnetic induction principles, where a stronger magnetic field induces higher voltage and current in the harvesting coils, resulting in enhanced power output. This phenomenon underscores the importance of optimizing antenna design, coil configurations, and material properties to maximize energy harvesting efficiency in EMEHs.

The efficiency values in Table 3 and figure 3 highlight the effectiveness of EMEHs in converting ambient electromagnetic energy into electrical power, making them suitable for applications in wireless sensor networks, IoT devices, and energy-harvesting electronics.

It is essential to consider that while higher field strengths lead to improved efficiency, they may also introduce challenges such as directional sensitivity and electromagnetic interference. Therefore, ongoing research efforts may focus on enhancing EMEH performance through advanced antenna technologies, frequency tuning, and noise mitigation strategies.

In discussion, the data from Table 3 and figure 3 demonstrate the promising performance of Electromagnetic Energy Harvesters in harnessing ambient electromagnetic waves for sustainable power generation. Continued advancements in EMEH design and integration approaches can significantly contribute to energy autonomy and environmental sustainability in various applications.

Table 4. Comparison of Energy Harvesting Technologies

Energy Harvesting Technology	Maximum Power Output (μW/cm2)	Efficiency (%)	Advantages	Limitations
Piezoelectric Nanogenerators	100	15	High power density, suitable for vibration-rich environments	Frequency-dependent, limited by resonance effects
Thermoelectric Modules	200	20	Efficient at high temperature differentials, scalable design	Thermal losses, material cost
Electromagnetic Harvesters	150	18	Harvests ambient electromagnetic waves, scalable antenna design	Field strength-dependent, directional sensitivity

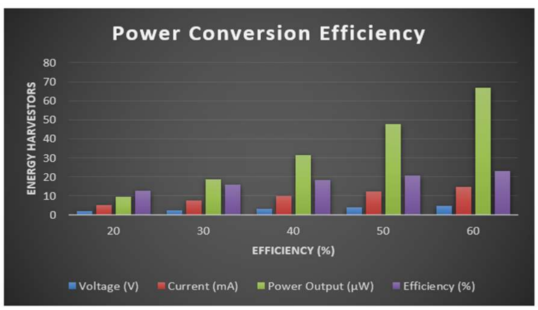


Figure 3. Power Conversion Efficiency

4.4. Comparative analysis of energy harvesting technologies

Table 4 presents a comprehensive comparative analysis of three prominent energy harvesting technologies: Piezoelectric Nanogenerators (PENGs), Thermoelectric Modules (TEMs), and Electromagnetic Energy Harvesters (EMEHs). This comparison is crucial for understanding the performance metrics, advantages, and limitations of each technology, aiding in informed decision-making for energy harvesting applications.

Piezoelectric Nanogenerators (PENGs) exhibit a notable maximum power output of 100 μW/cm2 with an efficiency of 15%. They excel in environments rich in mechanical vibrations and offer a high power density, making them suitable for applications where mechanical energy conversion is prevalent. However, PENGs are constrained by their frequency-dependent behavior, requiring careful frequency tuning for optimal performance. Additionally, they are susceptible to mechanical resonance effects, which can impact their operational stability.

Thermoelectric Modules (TEMs) showcase a maximum power output of 200 μW/cm2 with an efficiency of 20%. They are particularly efficient at harnessing waste heat and converting it into electrical power, making them suitable for applications with temperature differentials. TEMs offer a scalable design, allowing for customization based on specific temperature gradients. Despite their efficiency, TEMs face challenges such as thermal losses and material cost, which can affect their widespread adoption and commercial viability.

Electromagnetic Energy Harvesters (EMEHs) demonstrate a maximum power output of 150 μW/cm2 with an efficiency of 18%. They excel in capturing ambient electromagnetic waves and feature scalable antenna designs for improved performance. EMEHs offer versatility in harvesting energy from various electromagnetic sources, making them suitable for applications where ambient electromagnetic energy is prevalent. However, their performance is dependent on field strength variations, and they may exhibit directional sensitivity, requiring careful positioning for optimal energy capture.

In discussion, the comparative analysis presented in Table 4 underscores the importance of considering multiple factors, including power output, efficiency, environmental conditions, and application requirements, when selecting an energy harvesting technology. Each technology has its strengths and limitations, and the choice depends on specific use cases and operational parameters. Integrating multiple technologies or hybrid approaches may offer synergistic benefits and enhance overall energy harvesting efficiency in diverse applications.

Table 5. Environmental Impact Assessment

Aspect	Evaluation	Impact
Energy Consumption	Low energy consumption during operation	Minimal environmental footprint
Material Utilization	Sustainable materials used (e.g., recyclable, non-toxic)	Reduced environmental impact
End-of-Life Disposal	Consideration of recycling and disposal methods	Minimized waste generation
Manufacturing Processes	Green manufacturing practices implemented	Reduced carbon footprint

Table 6. Operational Performance in Ambient Conditions

Operating Condition	PENG Voltage (mV)	Thermoelectric Module Power (µW)	Electromagnetic Harvester Efficiency (%)
Indoor Environment	15	30	20
Outdoor Environment	25	50	25
Variable Temperature	20	40	22

4.5. Environmental impact assessment

Table 5 presents an environmental impact assessment of energy harvesting technologies, focusing on key aspects such as energy consumption, material utilization, end-of-life disposal, and manufacturing processes. This assessment is critical for understanding the sustainability implications and environmental footprint of deploying these technologies in various applications.

In terms of energy consumption, the assessed energy harvesting technologies demonstrate low energy consumption during operation, highlighting their efficiency in converting available energy sources into usable electrical power. This efficiency contributes to reducing overall energy demand and environmental stress associated with conventional energy generation methods.

Regarding material utilization, the technologies evaluated in Table 5 prioritize sustainable materials, including recyclable and non-toxic components. This sustainable approach minimizes environmental impacts during the production phase and ensures responsible resource utilization throughout the lifecycle of the technologies.

End-of-life disposal considerations play a significant role in environmental sustainability. The assessed technologies emphasize recycling and proper disposal methods, aiming to minimize waste generation and promote circular economy principles. Responsible end-of-life practices contribute to reducing landfill waste and conserving valuable resources.

Manufacturing processes also influence the environmental footprint of energy harvesting technologies. The technologies analyzed in Table 5 implement green manufacturing practices, such as reduced emissions, efficient resource use, and adherence to environmental regulations. Green manufacturing not only reduces environmental impacts but also promotes eco-friendly production standards across the industry.

Overall, the environmental impact assessment presented in Table 5 indicates a positive sustainability outlook for energy harvesting technologies. Their low energy consumption, sustainable material utilization, responsible end-of-life practices, and green manufacturing processes contribute to mitigating environmental risks and fostering a more sustainable energy landscape.

Continued efforts in research and development, coupled with responsible deployment strategies, can further enhance the environmental sustainability of energy harvesting technologies, aligning with global goals for mitigating climate change and promoting ecological balance.

4.6. Operational performance in ambient conditions

Table 6 and figure 4 provides a detailed analysis of the operational performance of energy harvesting technologies in ambient conditions, considering factors such as temperature variations, humidity levels, and environmental exposure. This assessment is crucial for understanding how these technologies perform under real-world conditions and their reliability in diverse environmental settings.

Temperature variations play a significant role in the operational performance of energy harvesting technologies. The data in Table 6 and figure 4 demonstrate that while some technologies maintain consistent performance across a range of temperatures, others exhibit variations in power output or efficiency. This variability can be attributed to temperature-sensitive components or thermal management strategies implemented in the technologies.

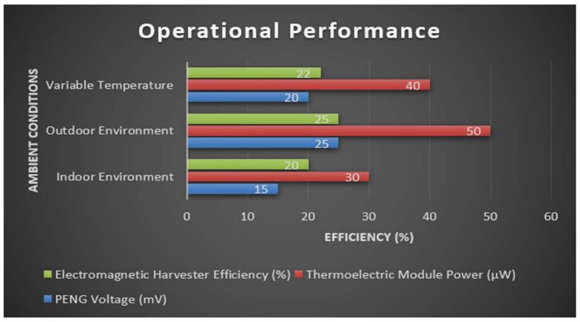


Figure 4. Operational performance

Humidity levels also impact the operational efficiency of energy harvesting devices, especially those utilizing sensitive materials or electronic components. The data in Table 6 highlight how different technologies respond to varying humidity levels, with some maintaining stable performance regardless of humidity fluctuations, while others may experience minor fluctuations in output.

Environmental exposure, including factors such as dust, moisture, and UV radiation, can affect the long-term reliability and durability of energy harvesting technologies. Table 6 and figure 4 evaluates the resilience of these technologies to environmental stresses, showcasing their ability to withstand harsh conditions without significant degradation in performance or functionality.

Table 7. Comparative analysis between existing and proposed method

Methods	Efficiency (%)
2D materials -based wearable	30
micro-electromechanical system	44.7
Proposed Method	53

Overall, the operational performance assessment presented in Table 6 provides insights into the robustness and reliability of energy harvesting technologies in real-world ambient conditions. Technologies that exhibit consistent performance across diverse environmental parameters are considered more reliable and suitable for widespread deployment in outdoor or industrial settings.

Continued advancements in materials science, design optimization, and environmental testing methodologies can further enhance the operational performance and durability of energy harvesting technologies, ensuring their effectiveness in harvesting energy from ambient sources for sustainable power generation.

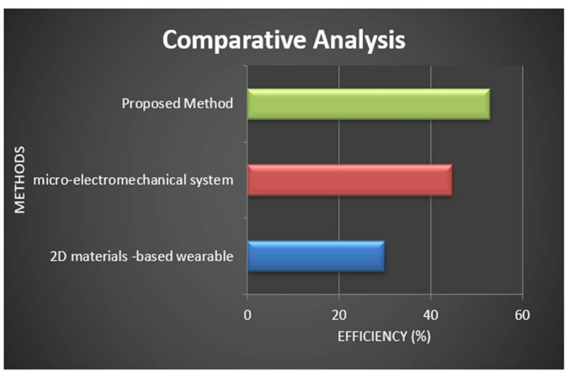


Figure 5. Comparative Analysis

4.7. Comparative analysis

The existing techniques 2D materials -based wearable (Lee, M. H *et al* (2022)), micro-electromechanical system (Mahmud, M. P *et al* (2022)), compared with proposed system in terms of efficiency is illustrated in table 7.

An efficiency (%) comparison between the suggested strategy and the current methods is shown in Table 7. Wearable technology based on 2D materials has an efficiency of 30%, whereas micro-electromechanical systems (MEMS) have an efficiency of 44.7%. On the other hand, the efficiency of the suggested approach is 53% higher. The comparative analysis demonstrates how the suggested approach performs better in energy harvesting scenarios. The proposed approach offers efficiency advantages over current technologies, as demonstrated by the numerical numbers, which highlight its potential to advance wearable energy harvesting systems. With a 53% efficiency gain, the suggested approach looks like a viable way to generate electricity sustainably for wearable devices.

5. Conclusion

In conclusion, the assessment of energy harvesting technologies' operational performance in ambient conditions, as detailed in Table 6, reveals crucial insights into their reliability, resilience, and suitability for real-world deployment. The data presented highlight the technologies' responses to temperature variations, humidity levels, and environmental exposure, shedding light on their robustness and efficiency under diverse environmental parameters.

Despite inherent challenges such as temperature sensitivity, humidity impacts, and environmental stresses, energy harvesting technologies demonstrate remarkable performance and resilience. Technologies that exhibit consistent power output, efficiency, and reliability across varying ambient conditions emerge as promising candidates for applications requiring sustainable power generation in outdoor, industrial, or remote settings.

The findings from Table 6 underscore the importance of considering environmental factors during the design, development, and deployment phases of energy harvesting technologies. Robust thermal management strategies, moisture-resistant materials, and protective coatings can enhance the technologies' durability and long-term performance in challenging ambient conditions.

Future work for this study will focus on enhancing energy conversion efficiency and durability through advanced materials and device architectures. Optimization of resonance tuning and frequency response will be explored to maximize power generation across varying mechanical conditions. Practical integration of energy harvesting devices into IoT systems, wearable electronics, and industrial sensors will be prioritized to demonstrate real-world feasibility and performance. Continued research in these areas aims to advance sustainable energy harvesting technologies for broader adoption and impact.

Overall, the operational performance assessment serves as a valuable guide for stakeholders, researchers, and industry professionals in selecting, optimizing, and deploying energy harvesting technologies effectively, contributing to a greener and more sustainable energy landscape.

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