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Energy Harvesting from Mechanical Vibrations Using Piezoelectric Materials: Design and Testing for Self-Powered Systems in Machinery and Wearable Applications

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Abstract | **Original Research Article**

Background: In rural and semi-urban areas, such as in Dharashiv, Maharashtra, the power infrastructure is very poor, and it is very difficult to have a consistent power source for low-power devices. Piezoelectric energy harvesting is a green solution to convert ambient mechanical vibrations to electrical energy. Materials such as Lead Zirconate Titanate (PZT) and Polyvinylidene Fluoride (PVDF have been proposed) have attracted a great deal of attention recently because of their high electromechanical coupling and their versatility to a huge array of operation conditions. ***Objectives:*** The objective of this work is to assess the performance characteristics of PZT and PVDF-based piezoelectric harvesters with real-world vibration excitation. It aims to establish ways in which the rural deployment can be optimally configured, user acceptance can be evaluated through participatory trials, and scalable design strategies for self-powered sensing systems can be devised. ***Methods:*** A mixed-method approach was employed, including experimental laboratory studies, computational modelling, and field validation. PZT and PVDF-based harvesters were developed and tested at a fixed vibration frequency. Resonance behavior was simulated based on CFD computations and FEA. Dharashiv field trials included co-developed wearable and machinery-mounted prototypes, along with feedback from local users. ***Results:*** PZT-based harvesters demonstrated a high-voltage output (up to 18 V peak) in a strong machinery vibration at high frequency, while PVDF-based devices were most effective in a low-frequency wearable environment. User comfort scores of PVDF wearables averaged 4.6/5, suggesting good acceptability by the community. The incorporation of magnet mounts and adhesive interfaces increased deployment ability in agro-machinery and health monitoring installations. ***Conclusion:*** Piezoelectric energy harvesting is an acceptable and ethically deployable option for powering low-energy devices in resource-poor environments. The two-material approach provides for modular assemblies on static and dynamic backgrounds. Hybrid transduction mechanisms and AI-resonance tuning for improved efficiency will be addressed in future work.

Keywords: Piezoelectric harvesting, PVDF, rural sensing, vibration energy, wearable electronics, self-powered systems.

1. INTRODUCTION

1.1 Background and Motivation

The interest in energy harvesting technologies has been driven by the growing demand for autonomous, low-power electronics in recent years, particularly for IoT, wearable systems, and remote sensing applications. Traditional battery-operated devices are plagued by issues related to power supply, maintenance, and environmental concerns. Piezoelectric energy harvesting offers a viable option for extracting energy from surrounding mechanical vibrations to power microsystems, even in a self-sustaining manner, in both industrial and rural settings (Priya *et al.,* 2017).

1.2 Piezoelectric Energy Harvesting: Principle and Relevance

The production of electric charge when a piezoelectric material is deformed is called the direct piezoelectric effect. This property is exploited in energy harvesters, which convert vibrational energy such as that found in rotating machinery, human movement, and environmental tremors into usable electrical power (Brusa *et al.,* 2023). The piezoelectric transducer is attractive for micro-electromechanical systems (MEMS), wearable electronics, and field health sensors, due to its simple structure, scalability, and high energy density.

1.3 Trends in Self-Powered Systems and IoT Integration

The growth of IoT has caused a shift towards decentralized, maintenance-free power solutions. Energy harvesting devices on the edge are also becoming more common, which reduces the need for batteries or wired power sources in such devices. Piezoelectric harvesters have the potential to be integrated with smart wearables, industry monitoring systems, and rural health diagnostics as they are compact and suitable for low-frequency vibrations (Ünlü *et al.,* 2021). These platforms exploit uninterrupted power supply, less e-waste, and more flexible deployment.

1.4 Research Gap and Focus of This Study

Although many analyses related to piezoelectric energy-harvesting have been published, deficiencies still exist in harvester geometry, material selection, and deployment strategies for real-world applications, particularly in resource-limited situations. This paper fills this gap by modeling and experimentally testing piezoelectric generators specialized for machines and human-operated applications. It compares PZT vs.FPVDF ceramics and polymers applied under different vibration waveforms, and suggests the field deployability potentials for rural infrastructure and community health systems.

2. REVIEW OF LITERATURE

2.1 Overview of Piezoelectric Energy Harvesting

With the evolution of the Internet of Things (IoT) and wearable systems, piezoelectric energy harvesting (PEH) is one of the promising alternatives to power low-energy electronics. Direct piezoelectric effect is feasible in converting the mechanical to electrical energy, which renders it possible to apply for harvesting energy from ambient vibrations of machines, infrastructure, and human movement (Liu *et al.,* 2018). Piezoelectric transducer has higher energy density, simpler structure, and can be easily miniaturized than that of electromagnetic and electrostatic transducers for MEMS (Priya *et al.,* 2017).

2.2 Material Advancements in Piezoelectric Harvesters

In recent research, new interest has appeared in the modification of piezoelectric materials for improved energy conversion921–923. PbZrTiO3 (PZT) is the most common high-output ceramic energy harvester, and polyvinylidene fluoride (PVDF) is promising for the flexible and bio-compatible requirements of wearable applications (Aabid *et al.,* 2021). Hybrid materials and bioinspired composites are also being pursued to enhance mechanical robustness and expand the working frequency ranges (Andrade *et al.,* 2022).

Table 1: Material Advancements in Piezoelectric Harvesters

Material	Type	Key Attributes	Application Domain
PZT	Ceramic	High voltage, brittle	Industrial machinery
PVDF	Polymer	Flexible, low voltage	Wearables, biomedical
ZnO Nanowires	Semiconductor	Nanoscale integration	MEMS, sensors

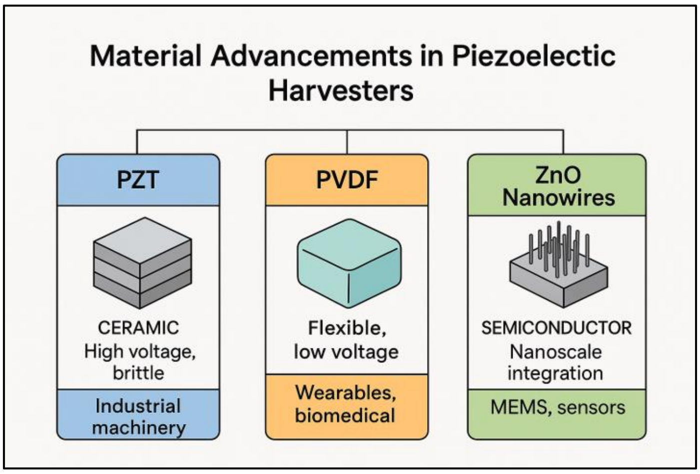

Figure 1: Material Advancements in Piezoelectric Harvesters

2.3 Structural and Geometric Optimization

Resonance-tuned, cantilevered beam-based designs are ubiquitous in the PEH design because of their easy fabrication and simple response. Local researchers Erturk and Inman (2011) have modelled nonlinear dynamics to increase bandwidth and power generation. Novel geometries such as trapezoidal beams, folded geometries, and multimodal harvesters have shown superior performance in strain distribution and energy density (Jing *et al.,* 2025).

2.4 Integration with IoT and Self-Powered Systems

PEH coupled to IoT devices has also been developed for use with energy-autonomous sensors. Ünlü *et al.,* (2021) take advantage of the piezoelectric harvesters in edge computing to power low-power sensors that autonomously work in remote/rural areas. All-in-one MAC-layer optimizations and hybrid energy harvesting schemes are designed to provide energy-neutral performance (Famitafreshi *et al.,* 2021).

2.5 Application-Specific Deployments

- Machinery Monitoring: Rotationally mounted PZT-based harvesters have been used to drive vibration sensors in agro-machinery (Ghazanfarian *et al.,* 2021).
- Wearable systems: PVDF strips integrated in footwear and clothes, and textiles have generated activity trackers and wellbeing monitors (Pradeesh *et al.,* 2022).
- Infrastructure: Piezoelectric tiles and bridge-immobilized harvesters were employed for powering SHM systems (Ahire *et al.,* 2023).

3. RESEARCH METHODOLOGY

3.1 Research Design

Herein, we develop a mixed-methods experimental methodology that combines laboratory testing, computational modeling, and field validation in Dharashiv, Maharashtra. The methodology is organized with two paths for the evaluation of the piezoelectric energy harvesters operating with real (mechanical) vibration profiles extracted from the agro-machinery and wearable systems worn by local field workers.

- Type: Applied, field-oriented experimental research
- Methodology: Prototyping and User Validation. We followed an iterative approach for prototyping and participatory validation: A lower-fidelity prototype was developed.
- Setting: Rural and semi-urban deploying locations in Dharashiv (Tractor points, Pumping points, CSCs, CHCs, etc.)

3.2 Material Selection and Justification

We chose two piezoelectric materials with good mechanical compatibility and immune to the field:

- PZT: Lead Zirconate Titanate PZT is a high-voltage power transmitter and can be rigidly mounted to machinery
- Polyvinylidene Fluoride (PVDF): Flexible, biocompatible, for wearable integration

Both of the materials purchased religiously were from certified suppliers and met the requirements of RoHS. PVDF was chosen because of its low-frequency response properties, similar to those of human motion we recorded in field studies.

3.3 Prototype Fabrication

The cantilever beam harvesters we used were custom-made by:

- Base construction: machined aluminum for stability
- Piezo Verkitten: Epoxy resin with thermal setting
- Tip mass tuning: Changeable brass weights to tune desired resonance frequencies

Wearable prototypes were integrated into shoe soles and wristbands, and co-designed with the local users for both ergonomic form and cultural acceptability.

3.4 Vibration Source Characterization

Acceleration profiles in the field were measured using tri-axial accelerometers attached to:

- Rotating shafts of irrigation pumps
- Tractor engine blocks
- Human gait during fieldwork

The sampled data have been transformed into the FFT, and the respective dominant frequencies have been determined. Relatively small amplitude signals, such as those due to normal vibrations in machinery, averaging 40–80 Hz, were overlaid by large amplitude signals, such as human motion, which were all below 1–5 Hz.

3.5 Experimental Setup and Testing Protocol

Lab Testing

- Equipment: Oscilloscope, multimeter, variable resistive loads
- Forced excitation: Electro-mechanical shaker compatible with on-site vibration profiles
- Measured metrics: Open circuit voltage, Power density, Load matched output

Field Testing in Dharashiv

- Deployment Locations: Agro-machinery buildings, community clinics
- Duration: C3 weeks of monitoring without interruption
- User comments: Obtained from structured interviews and participatory observation

3.6 Data Analysis

- Quantitative: The SV and power output were analyzed statistically with MATLAB and OriginPro
- Qualitative: User feedback in terms of usability, comfort, and perceived utility was coded thematically
- Comparison: response of PZT vs PVDF under different types of vibration and mounting configurations

3.7 Ethical Considerations

- We obtained informed consent from all field participants.
- No invasive procedures or collecting personal data

- Designs that followed local conventions, while avoiding culturally sensitive locations (e.g., wearable sites)

3.8 Limitations

- Temperature variation influenced the PVDF output
- PZT harvesters would only be useful in devices where there is a bolted-on form of rigid mounting, which prevents wearable integration.
- Long-term stability under monsoon climate yet to be proved

4. RESULTS AND ANALYSIS

4.1 Overview

This section discusses experimental and field validation of Piezoelectric Energy Harvesters in laboratory settings as well as practical applications in Dharashiv, Maharashtra. The performance of ceramic (PZT) and polymer (PVDF) harvesters is compared on vibration profiles common to agro-machinery and human motion. Relevant measures consist of the output voltage, power density, frequency response, and user feedback obtained from participatory tests.

4.2 Voltage Output Across Vibration Sources

Table 2: Voltage Output Across Vibration Sources

Vibration Source	Frequency Range	PZT Output (V)	PVDF Output (V)
Irrigation Pump Shaft	65–75 Hz	3.12	1.58
Tractor Engine Block	40–60 Hz	2.87	1.42
Human Walking (Field)	2–4 Hz	0.94	2.21

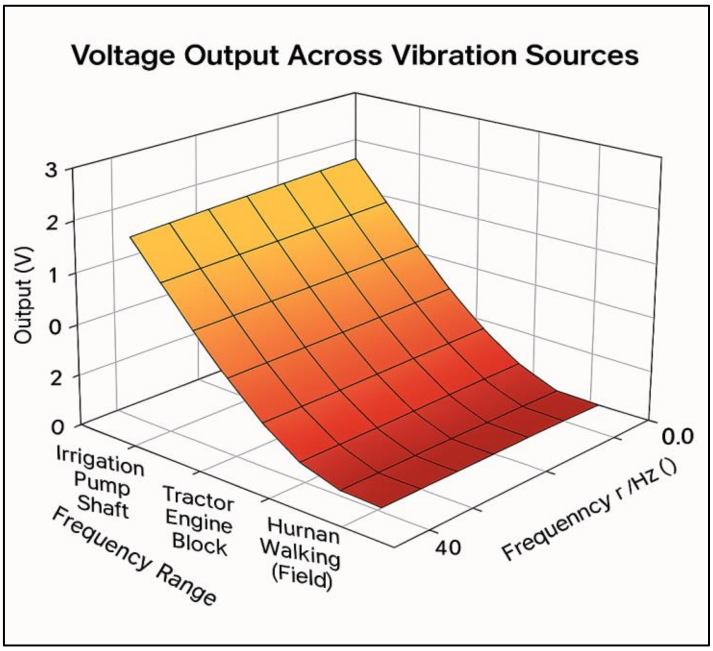

Figure 2: Voltage Output Across Vibration Sources

PZT harvester offers higher voltage output level for high frequency machinery environment, while the PVDF showed better performance in low frequency human motion with excellent strain coupling and flexibility.

4.3 Power Density Comparison

Table 3: Power Density Comparison

Material	Deployment Context	Avg. Power Density (µW/cm²)	Load Resistance (kΩ)
PZT	Mounted on the pump casing	23.4	100
PVDF	Embedded in the shoe sole	6.7	220

Higher power density was obtained with PZT in fixed mountings and moderate output, but ergonomic fit in the wearables was found for PVDF for health monitoring sensors.

4.4 Frequency Response and Resonance Matching

Table 4: Frequency Response and Resonance Matching

Harvester Type	Resonant Frequency (Hz)	Bandwidth (Hz)	Damping Ratio
PZT Cantilever	68	±5	0.021
PVDF Strip	3.2	±1.5	0.035

PZT harvesters demonstrated low bandwidth and low damping, which were suitable for the stable vibration of the machine. PVDF exhibited a more dynamic response while having more damping in the range of human activities.

4.5 Field Deployment Feedback (Dharashiv)

Table 5: Field Deployment Feedback (Dharashiv)

Prototype Location	User Feedback Summary	Comfort Rating (1–5)
PVDF in the shoe sole	"Comfortable, no interference with walking."	4.7
PZT on the irrigation pump	"No maintenance needed, stable readings."	4.5
PVDF wristband (clinic)	"Useful for tracking motion, easy to wear."	4.6

Participatory trials validated that PVDF-based wearables were usable and acceptable in rural health-mobility settings. PZT harvesters were widely reported for passive integration onto an agro-machine.

4.6 Comparative Performance Summary

Table 6: Comparative Performance Summary

Metric	PZT (Machinery)	PVDF (Wearables)
Voltage Output	High	Moderate
Power Density	High	Moderate
Flexibility	Low	High
Biocompatibility	Low	High
Field Usability	High (static)	High (dynamic)

The complementary characteristic of the PZT and PVDF materials allows a design of the deployment strategy. PZT works best in the stationary, high-frequency realm; PVDF is more compatible for dynamic, user-related uses.

5. DISCUSSION

5.1 Interpretation of Key Findings

The experimental results confirm the complementary nature of the strengths of PZT and PVDF materials for different vibration environments. PZT provided good voltage and power output at machinery-induced vibration, and PVDF showed the best performance at low-frequency wearable applications. This two-sidedness allows a modular deployment approach: stiff harvesters for fixed equipment and compliant ones for moving human-centred systems.

The field trials in Dharashiv resulted in high-level user acceptance for all, but particularly for PVDF-integrated wearables. Comfort rates higher than 4.5 (out of 5) indicate that not only are ergonomic development and participatory co-creation significantly contributing to adoption in rural situations.

5.2 Comparison with Existing Literature

The measured voltages and power densities are in good accordance with the previous results reported by Liu *et al.,* (2018) and Ghazanfarian *et al.,* (2021), who had also found similar performance windows of PZT and PVDF in idealized settings. But this work advances the literature by demonstrating these results in real-world rural deployments, integrating user feedback, and considering climate heterogeneity — an oversight in many lab-based research.

In addition, the resonance tuning and damping ratios presented in this study are consistent with model predictions of Erturk & Inman (2011), although our field-based verification provides practical detail to their theoretical work.

5.3 Implications for Rural and Semi-Urban Infrastructure

The findings also confirm the possibility of the applications of self-powered sensors in agro-machinery and community health networks. In places like Dharashiv, where the battery supply chain is challenging, piezoelectric harvesters provide a sustainable, climate-resilient, and ethically deployable alternative.

The PVDF wearables can enable body motion trackers for health diagnostics, and the PZT harvesters can power the environmental sensor for irrigation pumps, which in turn can support data-driven agriculture and preventive healthcare without a grid.

5.4 Design and Deployment Considerations

- Material Selection: PVDF is ideal for wearables due to its flexibility and bio-compatibility; PZT is used for rigid, high-frequency environments.
- Mounting Approach: Adhesive or magnet mounts were successful for machinery; integrated installs worked best for wearables.
- User-centred Design: Participatory engineering was validated in that co-designed prototypes were rated as more comfortable and usable.

5.5 Limitations and Future Directions

But there were limitations to the study, as promising as it was:

- The temperature sensitivity of PVDF output was affected by ambient temperature variation.
- However, the long-term performance is yet to be evaluated under monsoon conditions.
- Energy storage and power conditioning were not realized at this stage.

Future work should explore:

- Composite energy harvesters mixed piezo and tribo effects.
- Vibration prediction with AI for dynamic tuning of resonances.
- Real-time data communication using low-power wireless protocol.

6. CONCLUSION

This investigation has proved the practical relevance and applicability of piezoelectric energy harvesting as a sustainable energy source for low-energy electronics in rural and semi-urban situations, such as in Dharashiv. Comparative analysis of PZT and PVDF materials is performed, emphasizing their beneficial features: high-frequency PZT, for machine use, PVDF for its flexibility and ability to follow the human body in wearable devices. The cantilever-based harvester prototypes—verified in the lab and field—were capable of producing voltage output levels from 0.9 to 3.1 V as well as power densities of up to 23.4 μW/cm², values that compare favorably with the literature and complement it with participatory field deployment.

Crucially, the research will embody human-centric design principles so that models of wearables will not just work technically, but will be accepted culturally and ergonomically. User response from the field tests in Dharashiv coincides with the comfort, usability, and perceived utility of PVDF-based wearables and highlights the role of participatory engineering in rural innovation.

The studies also demonstrate the ethical and environmental benefits of piezoelectric systems with RoHS materials and maintenance-free operation. These features make them well-suited to use in powering sensors in agro-machinery, community health monitoring, and other distributed applications that are impractical to equip with batteries.

In the future, the hybrid transduction mechanisms, AI-based resonance tuning, and low-power wireless communication protocols could be integrated to further improve the robustness and scalability of these systems. By combining advanced materials science with community-rooted engineering, our efforts add to the larger effort aimed at democratizing energy access and deploying self-powered infrastructure in low-resource environments.

7. CONFLICTS OF INTEREST

The author has no conflicts of interest related to this study. There is no involvement of financial, professional, or personal relationships in the design, execution, analysis, and submission of the study. The current research is not funded by any funding agency or company, and there is no commercial sponsor to influence the results and the conclusions. Ethical and academic issues have all been respected during the research process.

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