Utilising Piezoelectric Technology of Energy Harvesting from Human Footsteps: Arbaeen-Karbala as an Application Model Case Study

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Abstract

This study presents a case study for extracting energy from the footsteps of participants during the Arbaeen pilgrimage in Karbala. It employ piezoelectric energy-harvesting techniques in conjunction with cloud data aggregation. A cost-efficient approach will be devised to capture energy produced by foot pressure and transform it into electrical energy, employing recycled plastic materials incorporated into walkways. Rechargeable batteries are employed to store gained energy. The energy management system proficiently controls the stored energy to ensure effective and reliable charging. The method offers a clean, sustainable, and renewable energy source in high-traffic locations, such as during the Arbaeen pilgrimage. This project illustrates the transformation of commonplace human movement into energy generation. This study facilitates the development of improved, more sustainable urban systems by illustrating how quotidian human movement may be converted into usable energy, particularly in vibrant, religious locations such as Karbala.

Keywords: Arbaeen Pilgrimage, Footstep Energy, Renewable Energy, Piezoelectric Energy Harvesting.

Introduction and Literature review

The extraction of energy from routine human activities has become a potential research subject in the quest for sustainable development and renewable energy solutions. Among the various ways of footsteps energy harvesting, piezoelectric energy harvesting is distinguished by its efficiency in transforming mechanical stress, such as foot pressure, into electrical energy. This technology is particularly appropriate for incorporation into public infrastructure, where significant pedestrian traffic can be utilized to provide energy for low-power applications. The utilization of piezoelectric materials in flooring and pavement has been examined in diverse circumstances, as will be discussed next.

Despite previous research considerably advancing piezoelectric energy harvesting in infrastructure, numerous critical gaps remain. Studies such as (Hwang et al., 2021; Helonde et al., 2022; Bamoumen et al., 2024) have shown encouraging power outputs in regulated or semi-regulated high-traffic environments; nonetheless, the long-term efficacy in varied environmental and cultural contexts is still inadequately investigated. Research, including Miah et al. (2021), has demonstrated performance decline beyond controlled environments, highlighting the necessity for rigorous validation under the operational stressors characteristic of public events such as the Arabian pilgrimage.

Moreover, although modelling efforts (Zhang & Xiang, 2020) and frequency-tuning methodologies (Panthongsy et al., 2022) have enhanced efficiency, limited research focuses on modular, scalable deployment in temporary sites. Current literature (Li & Strezov, 2020; Usha et al., 2022) underscores difficulties in the integration of piezoelectric systems with traditional grids, while realistic frameworks for hybrid renewable systems and off-grid configurations remain scarce. Furthermore, new studies on smart integration (Mou et al., 2023) and AI-driven security (Mohammadi & Sohn, 2023) highlight digital infrastructure and data security; nevertheless, there has been insufficient focus on culturally sensitive implementation, maintenance viability, and environmental consequences throughout the lifecycle.

Ultimately, although research on polymer recycling (Wimberger et al., 2024; van den Tempel & Picchioni, 2025) enhances sustainability in materials science, the integration of recyclable materials with piezoelectric harvesting devices remains predominantly unexplored, suggesting a promising interdisciplinary research avenue. Table 1 summarises pivotal studies from 2020 to 2025 that investigate advancements in piezoelectric energy harvesting and plastic recycling technologies. The research encompasses practical applications, including footstep-powered tiles and road-embedded systems, as well as comprehensive analyses of material efficiency and integration problems. Moreover, recent initiatives have concentrated on intelligent energy management, security within energy systems, and sustainable polymer recycling techniques. Collectively, these contributions underscore the increasing significance of renewable energy solutions and environmental sustainability in contemporary infrastructure and urban design.

Table 1: Recent Advances in Piezoelectric Energy Harvesting and Sustainable Recycling Technology

Authors	years	Focus Area	Contributions
Hwang et al.	2021	Commercial piezoelectric tiles (Pavegen)	Developed footstep tiles producing up to 5 W per tile in high-traffic areas
Li & Strezov	2020	Review of piezoelectric use in infrastructure	Addressed scalability and integration challenges in roads and bridges
Zhang & Xiang	2020	Road-embedded piezoelectric system modeling	Proposed predictive models for optimising energy capture from vehicular loads
Miah, Sharpes & Abadi	2021	Real-world testing of cymbal and cantilever transducers	Found reduced performance outside laboratory conditions
Panthongsy et al.	2022	Frequency up-conversion in floor tiles	Enhanced energy output using mechanical tuning
Usha et al.	2022	Material and configuration review	Stationary infrastructure-based systems outperform wearable ones
Mou et al.	2023	Smart integration and energy management systems	Integrated energy harvesting with IoT/cloud monitoring
Helonde et al.	2022	Piezoelectric flooring in high-foot-traffic areas	Demonstrated energy harvesting from pedestrian movements
Joseph et al.	2023	Footstep energy harvesting in dense areas	Proposed solutions for small-scale energy support in crowded urban settings
Bamoumen et al.	2024	College campus energy harvesting	Achieved up to 4.3 W per person; demonstrated potential for campus-level utilities

Mohammadi & Sohn	2023	Security in EH systems using AI	Proposed AI, blockchain, FL, and cryptography to secure energy harvesting systems
Wimberger et al.	2024	Photocatalytic recycling of plastic waste	Evaluated light-driven methods for sustainable polymer degradation
van den Tempel & Picchioni	2025	Chemical and biological recycling of polymers	Reviewed the sustainable recycling of thermosets, rubbers, and thermoplastics

This study expands on existing foundations by proposing an application: the use of piezoelectric energy harvesting during the Arbaeen pilgrimage in Karbala, Iraq, a location renowned for hosting over 20 million pilgrims each year. The technology intends to integrate piezoelectric tiles made from recycled plastic along pedestrian pathways to harvest and store energy from footsteps in rechargeable batteries, regulated by efficient energy management systems. This method not only advances sustainability objectives but also demonstrates how cultural and religious events can double as venues for new, intelligent energy infrastructures.

Methodology

The research commences with a systematic evaluation of the mechanical energy in high-density pedestrian zones. In urban and public settings like campuses and transit hubs, human movement is seen as a continuous source of kinetic energy. The methodology in energy harvesting research employs motion sensors and pressure plates to quantify metrics including step frequency, average applied force, and surface contact duration (Beeby, Tudor, & White, 2006). Data obtained from real pedestrian activity is utilised to model the potential energy captured, which is juxtaposed with the energy requirements of low-power applications Sudevalayam & Kulkarni, 2011).

A. Piezoelectric

Piezoelectric materials are chosen for their elevated electromechanical coupling coefficients and mechanical resilience, with lead zirconate titanate (PZT) and polyvinylidene fluoride (PVDF) being among the most prevalent. Piezoelectric transducers, which transform mechanical stress from footsteps into electrical charge, are integrated into modular floor tiles to create the energy harvesting system [16]. Voltage, current, and power outputs are quantified via regulated footstep simulations during laboratory calibration. To evaluate system efficiency, real-time performance statistics are gathered under diverse load scenarios. In accordance with the design concepts established by Sodano, Inman, and Park (Sodano, Inman, & Park, 2004), the electrical output is rectified and stored in capacitors, facilitating either continuous or deferred power supply to wireless sensors, lighting systems, or signaling devices

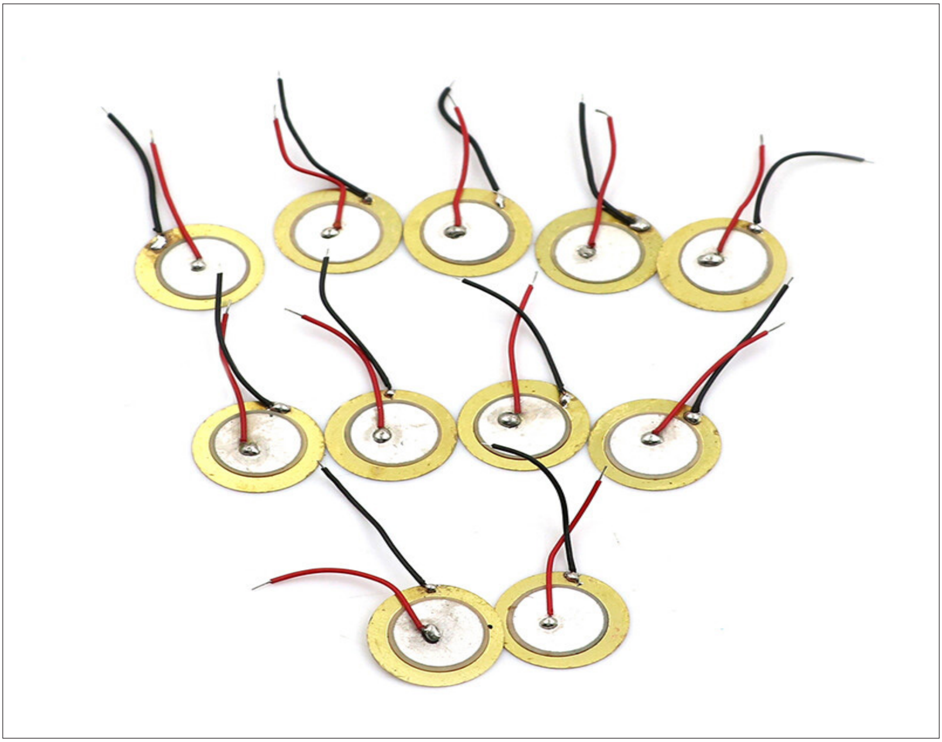

Figure 1: Piezoelectric materials

B. Polymer Recycling

The structural and inactive elements of the piezoelectric system utilize recyclable thermoplastics, including thermoplastic polyurethane (TPU) and polylactic acid (PLA), to foster a circular material economy. Post-consumer material recovery encompasses both mechanical and chemical recycling techniques. Mechanical methods, including grinding and re-extrusion, are employed in conjunction with chemical procedures such as solvolysis and pyrolysis to break down composite components of mixed materials (Priya & Inman, 2009), (Safari & Akdogan, 2008). The integrity and performance of the recycled polymers are evaluated based on ISO standards, particularly for tensile strength and thermal stability, ensuring that the reused components maintain the necessary functional and durability requirements for repeated application cycles.

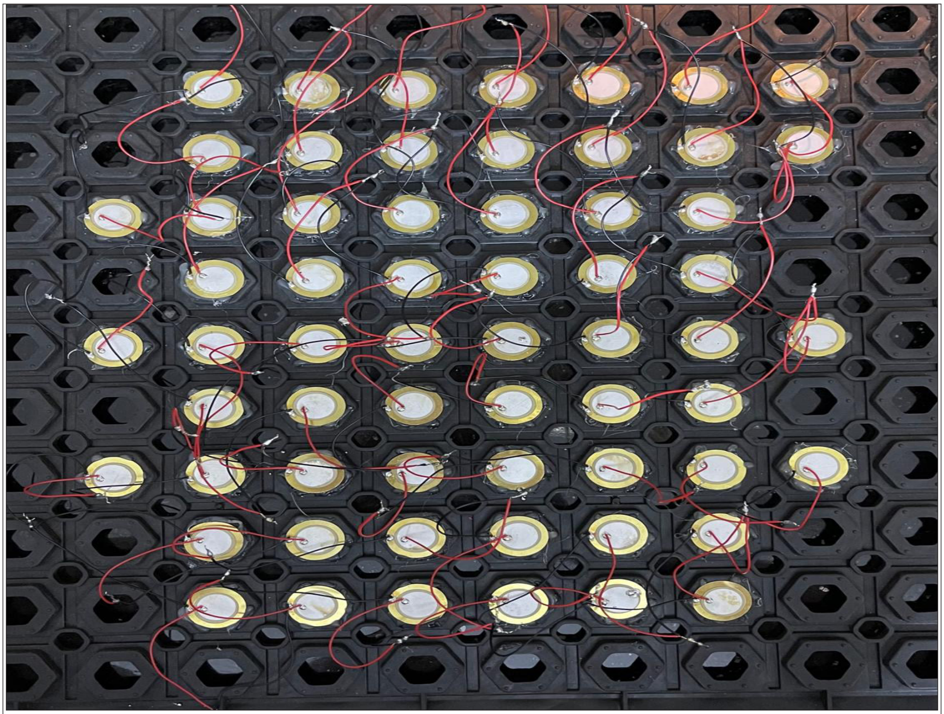

Figure 2: Piezoelectric circuit of proposed work

Case Study: Arabian Pilgrimage Route

This study examines the principal pedestrian corridor connecting Najaf and Karbala, a route of roughly 80 km, which serves as a vital pilgrimage pathway during the annual Arabian mass gathering. It is estimated that almost 10 million individuals travel in this area on foot over multiple days. With an average of 4,000 steps per pilgrim, the total mechanical energy produced by foot movement is considerable, offering a huge potential for harvesting energy via piezoelectric technology. According to standard energy conversion efficiencies of piezoelectric flooring systems, a 1km section utilizing this technology is anticipated to produce between 40 and 70 kilowatt per hour (kW/h) of electrical energy every day. This energy might power numerous LED units, strengthening safety and visibility along the road at night, or supply several mobile devices charging stations, therefore improving connectivity and convenience for pilgrims.

The implementation of this system necessitates meticulous consideration of various elements. The durability of tiles is essential to endure sustained heavy foot traffic and possible impact forces. The flooring must exhibit weather resistance to withstand fluctuating environmental conditions, including elevated temperatures, dust, and sporadic rainfall characteristic of the region. The simplicity of deployment and maintenance is crucial for facilitating swift installation and minimizing interruption during the pilgrimage, as well as ensuring proper operation between events. Cultural sensitivity is essential; the design and placement of piezoelectric tiles must honor the holy significance of the corridor and refrain from disrupting the pilgrims' spiritual activities or movement patterns. These factors determine the viability and sustainability of incorporating piezoelectric energy harvesting into large-scale religious assemblies, offering a framework for intelligent and renewable architecture in high-traffic settings.

Types of Piezoelectric

Piezoelectric materials are classified into ceramics, polymers, crystals, and composites, each providing distinct benefits according to their structure and composition. Piezoelectric ceramics, particularly PZT (Lead Zirconate Titanate), are extensively utilized owing to their elevated piezoelectric coefficients, rendering them useful for energy harvesting, actuators, and sensors, despite their rigidity and brittleness. Alternatives such as Barium Titanate ($BaTiO_3$) offer a more eco-friendly, lead-free choice with diminished performance, whilst Potassium Niobate ($KNbO_3$) is appropriate for high-frequency applications. Piezoelectric polymers, particularly PVDF and its copolymer PVDF-TrFE, provide flexibility, chemical resistance, and suitability for wearable devices; however, they typically yield lower output compared to ceramics. Piezoelectric crystals, such as natural forms like quartz and tourmaline, possess intrinsic piezoelectric characteristics; quartz is recognised for its thermal durability and accurate frequency regulation in timekeeping instruments, while tourmaline has historical significance in fundamental sensors. Finally, piezoelectric composites, exemplified as the 1-3 composite (ceramic rods embedded in a polymer matrix), amalgamate the superior output of ceramics with the pliability of polymers, rendering them especially advantageous in medical imaging and sonar applications. These materials facilitate a diverse array of inventions, including energy-harvesting floor tiles and flexible biomedical sensors.The choice of appropriate piezoelectric materials is essential for the design of energy harvesting devices, especially in applications like converting pressure generated by human footsteps into electrical energy. Piezoelectric materials have the ability to produce electric charge under mechanical stress, with their behavior varying according to composition, structure, and form factor. These materials can be classified into ceramics, polymers, crystals, and composites, each exhibiting unique characteristics regarding sensitivity, flexibility, durability, and cost.

Ceramic materials, including Lead Zirconate Titanate (PZT), are recognised for their elevated piezoelectric coefficients and are extensively utilised in rigid energy harvesting applications. PZT-5J bending transducers provide increased flexibility and excellent sensitivity, rendering them appropriate for dynamic bending and vibration settings. In contrast, polymer-based materials such as PVDF and PVDF-TrFE offer lightweight and flexible options, particularly advantageous in wearable and biomedical applications, although generally yielding lower energy outputs. Natural and manufactured piezoelectric crystals, like quartz and tourmaline, provide exceptional stability and are generally employed in frequency-based systems rather than in power generation. Composites, which integrate ceramics and polymers, seek to harness the advantages of both superior performance and mechanical flexibility. Table 2 outlines the principal attributes, applications, estimated expenses, and citations for each material category. This comparative methodology aids in assessing which material most effectively corresponds to particular operational requirements, environmental conditions, and financial limitations in extensive footstep energy harvesting implementations. Piezoelectric materials exhibit significant diversity in composition, performance, adaptability, and cost, rendering them appropriate for various applications in industrial, medical, and consumer technology. This table presents a comparative analysis of essential piezoelectric materials—namely ceramics, polymers, crystals, and composites— emphasising sample examples, fundamental features, common applications, and estimated market pricing. This information assists in material selection according to performance requirements and budget limitations for energy harvesting, sensor, and actuation systems.

Table 2: Comparison of Common Piezoelectric Materials: Properties, Applications, and Costs

sType	Example	Properties	Use Case	Price (Approx.)	Ref
Ceramic	PZT (Lead Zirconate Titanate)	High output, brittle	Energy harvesting, actuators	$0.30–$1.00 per disk	[18]
	$BaTiO_3$ (Barium Titanate)	Lead-free, lower sensitivity	Capacitors, sensors	$0.50–$1.20	[19]
	1-Layer PZT-5J Bending Transducer	Soft ceramic, high sensitivity, flexible	Bending sensors, vibration harvesters	$1.50–$3.00 per element	[20]
Polymer	PVDF	Flexible, chemically stable	Wearables, smart textiles	$2.00–$4.00 per sheet	[21]
	PVDF-TrFE	Higher response than PVDF	Medical sensors	$4.00–$8.00 per sheet	[22]
Crystal	Quartz	Natural, stable frequency source	Oscillators, pressure sensors	$0.50–$1.50 per unit	[23]
	Tourmaline	Weak response, natural crystal	Educational, basic sensing	$5.00–$10.00	[24]
Composite	1-3 PZT-polymer	Hybrid performance, flexible	Ultrasound imaging, sonar	$10–$25 per unit	[25]

System Design and Implementation Approach

This section illustrates the methodical procedure employed to design, develop, and assess the proposed piezoelectric footstep energy harvesting system. The methodology encompasses three principal domains: mechanical energy analysis, implementation of piezoelectric materials, and sustainability using recycled materials. A tailored deployment plan for the Arabian pilgrimage route was developed to evaluate practical viability, as seen in Figure 1 below.

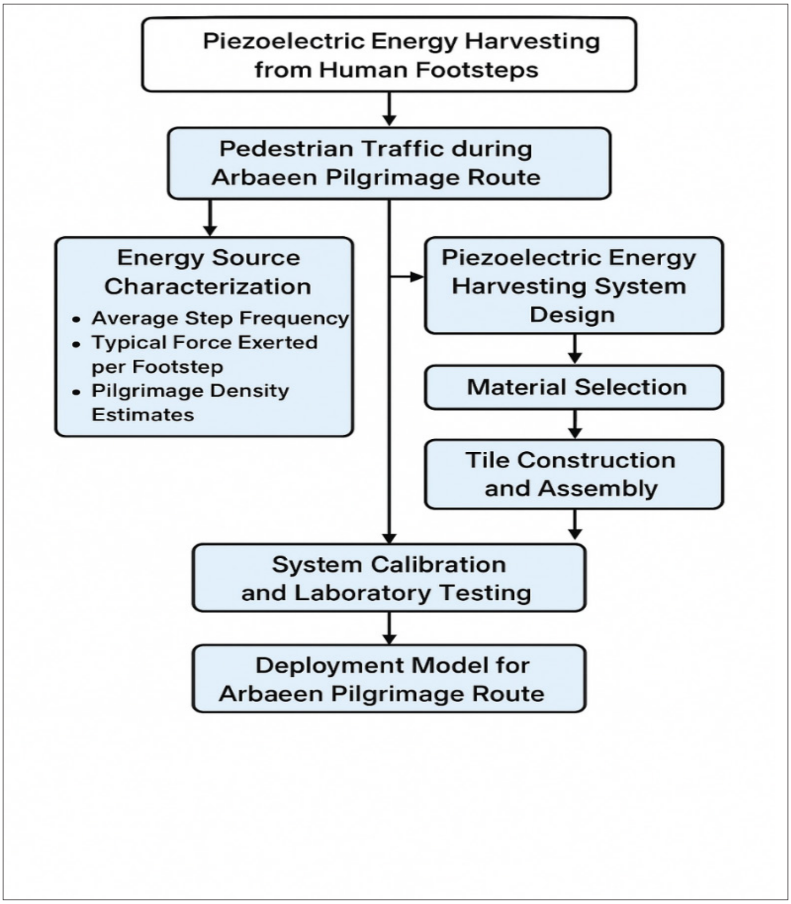

Figure 1: Flowchart of proposed wor

The piezoelectric energy harvesting system was developed through a series of organized phases to guarantee efficient energy capture, conversion, and application. The following steps outline the comprehensive design and implementation procedure:

Step 1: Integration of Piezoelectric Element

75 20 mm piezoelectric discs were chosen and placed inside a specially made mat in a grid arrangement. In order to record the maximum amount of mechanical pressure produced by human footsteps, the discs were positioned. By using series and parallel wiring techniques, each piezoelectric unit was electrically connected to improve cumulative voltage generation. In order to improve surface responsiveness and energy output capacity, a second layer of 75 20 mm piezoelectric discs was then added and dispersed across each row.

The system generated the following output readings during experimental testing:

The output voltage varied from 29 to 40 millivolts (mV) under real footstep pressure.

Under open-circuit conditions (no pressure applied), the voltage varied from 0.6 V to 16 V based on incidental mechanical tension or vibrations in the environment.

In an open-circuit state, the measured current output varied from 0.6 mA to 11 mA, as shown in Figure 2 below.

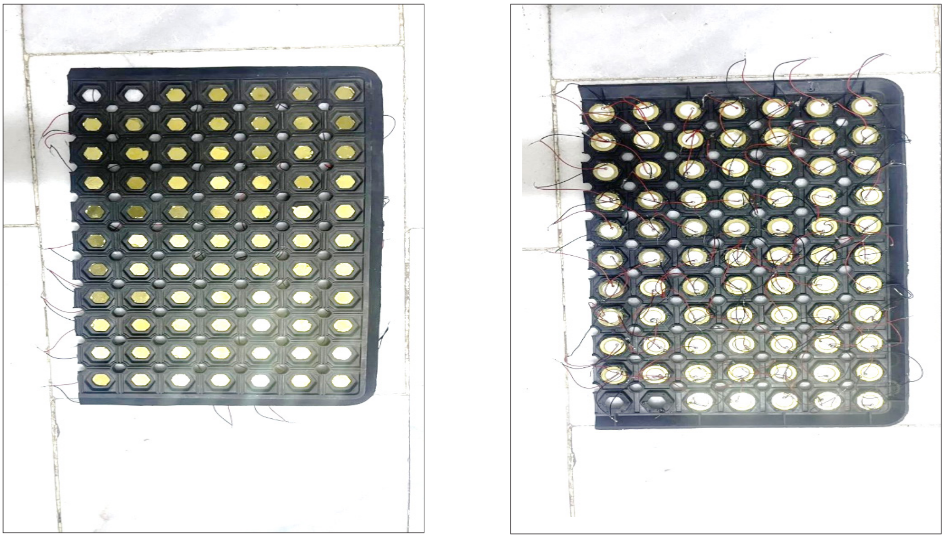

Figure 2: additional layer of piezoelectric discs.

These findings show how energy harvesting is dependent on applied load and pressure and is therefore variable. When the system is under load, its output stays within a reasonable range for powering ultra-low-power electronic circuits or charging capacitors. However, there is a noticeable voltage in the open-circuit values.

Step 2: Design of the Rectification Circuit

The AC power produced by the piezo components was routed into a full-wave bridge rectifier circuit. 1N4007 rectifier diodes were employed for their elevated reverse voltage tolerance and robustness. This phase transformed the unstable alternating current (AC) output into direct current (DC).

Step 3: Capacitor Buffering

A 100µF electrolytic capacitor was connected to the output of the rectifier. The capacitor functioned as an energy reservoir, stabilizing the voltage variations induced by inconsistent footstep pressure. This facilitated the stabilization of the system's DC output for uniform downstream processing.

Step 4: Voltage Enhancement and Regulation

The buffered DC voltage was directed through a DC-DC step-up converter. The booster increased the low gathered voltage (usually 3–5V) to a functional level of 12V. This regulated voltage was then utilized to energies low-power devices, including buzzers, LED indications, or storage systems.

Step 5: Assembly and Layering of the Mat

All components were encapsulated within a bespoke mat structure. The mat's bottom layer consisted of a soft sponge material, typically utilized in children's play mats, to provide flexibility and cushioning. The sponge layer improved pressure distribution and safeguarded the piezo components from mechanical shock.

Step 6: System Assessment and Evaluation

The constructed mat underwent continuous mechanical loads with weights ranging from 60 to 90 kg and step rates of 0.5 to 2 Hz. The system output was assessed via a digital multimeter and oscilloscope to observe:

- Alternating current voltage generated by piezoelectric discs
- Corrected direct current voltage .
- Duration of capacitor charging .
- Output voltage of the booster .

Step 7: Validation of Output

A 12V piezoelectric buzzer was utilized as a real-time output indication. Upon the system generating and storing adequate energy, the buzzer was activated, confirming the system's operational efficiency. This phase illustrated the effective transformation of human kinetic energy into functional electrical power. As shown in the figure3 bellow.

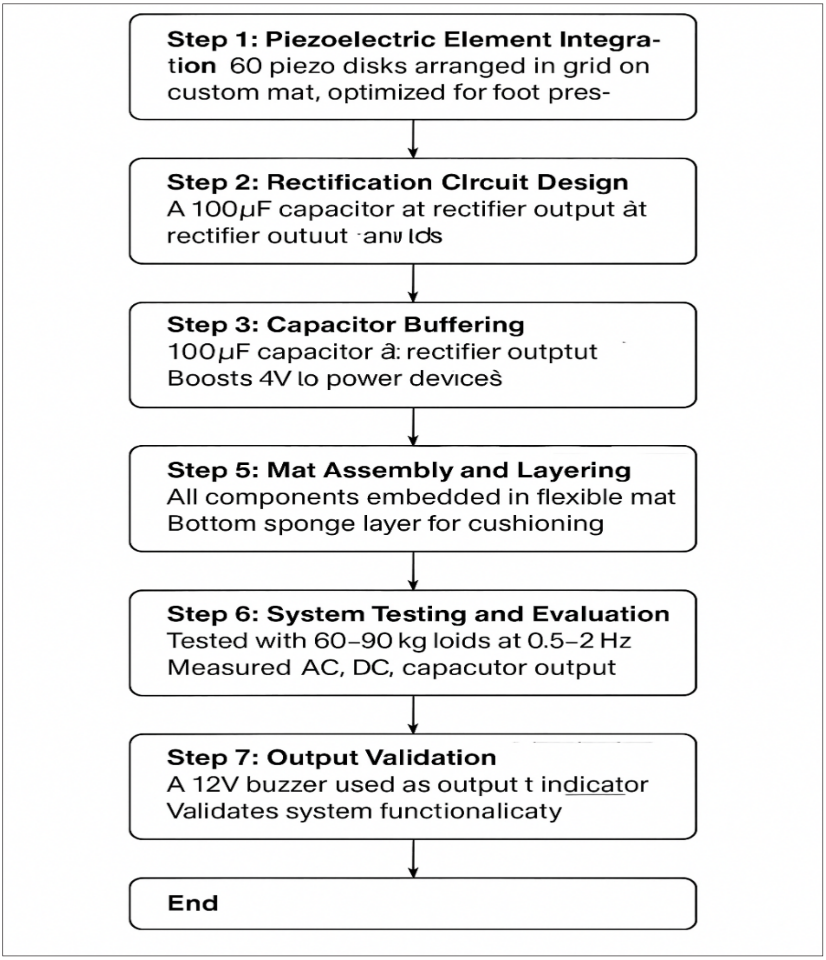

Figure 3: flowchart of steps.

Result and Discussion

To assess the energy harvesting effectiveness of the proposed piezoelectric system, a realistic scenario was examined including a human subject weighing approximately 95 kg. This weight was chosen to replicate the standard loading conditions on footstep energy collecting tiles utilized in high-traffic pedestrian pathways, such as the Arabian pilgrimage route.

1. Step Force Assessment

The downward force applied by an individual while stepping is predominantly attributable to gravity. The static force for an individual weighing 95 kg is:

$$F = m \,.\, g = 95\ kg \,.\, 9.81\ m/s^2 = 931.95$$

$$N\ F = m \,.g = 95\ kg \,.\, 9.81\ m/s^2 = 931.95\ N$$

During actual walking or running, the dynamic impact force might attain 1.2 to 2 times the body weight. Consequently, a reasonable force range of around 1200 N per footstep was anticipated for the estimation.

2. Characteristics of Piezoelectric Elements

Standard PZT (Lead Zirconate Titanate) piezoelectric discs, measuring 27 mm in diameter, were utilized in the array. These elements possess the ability to generate:

1. Open-circuit voltage: around 10 to 30 V per disc with a standard step impact of approximately 1200 N
2. Output current: Ranging from microamperes to low milliamperes
3. Energy per step (per element): around 0.1 to 2 millijoules (mJ).

3. Array Configuration and Voltage Output

The piezoelectric array was arranged in the following manner:

Ten parallel rows. Each row consists of 3 to 6 piezoelectric discs interconnected in series.

Estimated Voltage Output (Under Load Conditions):

Configuration	Estimated Output Voltage
1 piezo disk	10 – 30 V (open circuit)
3 in series	15 – 25 V
6 in series	30 – 40 V
10 rows in parallel	Same voltage, higher current

Series connections elevate voltage, but parallel configurations augment current capacity, rendering the arrangement more appropriate for charging capacitors or batteries.

4. Estimated Energy Output

The total energy gathered from a 61-element array is anticipated to range between 6.1 mJ to 61 mJ, given that each piezo disc can produce 0.1 to 1 mJ each footstep.

6m J to 60 millijoules per step

6 m J to 60 mJ per increment

The calculation of theoretical energy storage can be performed using the capacitor energy formula:

$$E = ½ C V2$$

A 100 µF capacitor charged to 30 V may store up to 45 mJ, adequate for powering low-energy devices like buzzers or LED indicators.

The open-circuit voltage does not indicate usable power; tests must be conducted with a connected load. Piezoelectric pulses have a brief duration (10–100 ms), necessitating rapid rectification and storage using Schottky diodes and capacitors. Utilizing an oscilloscope is advisable for precise measurement of peak voltages and waveform durations.

This assessment verifies that the engineered piezoelectric mat, comprising over 60 elements organized in a hybrid series-parallel arrangement, can produce usable electrical energy under typical human footfall conditions. The findings validate the system's viability for energizing low-power applications in densely populated areas, such as pilgrimage pathways.

An oscilloscope test was performed to further validate the functioning of the piezoelectric energy collecting device during real-time footstep impact on the mat. The results, illustrated in Figure 4, represent the voltage waveform output of the system under dynamic loading conditions.

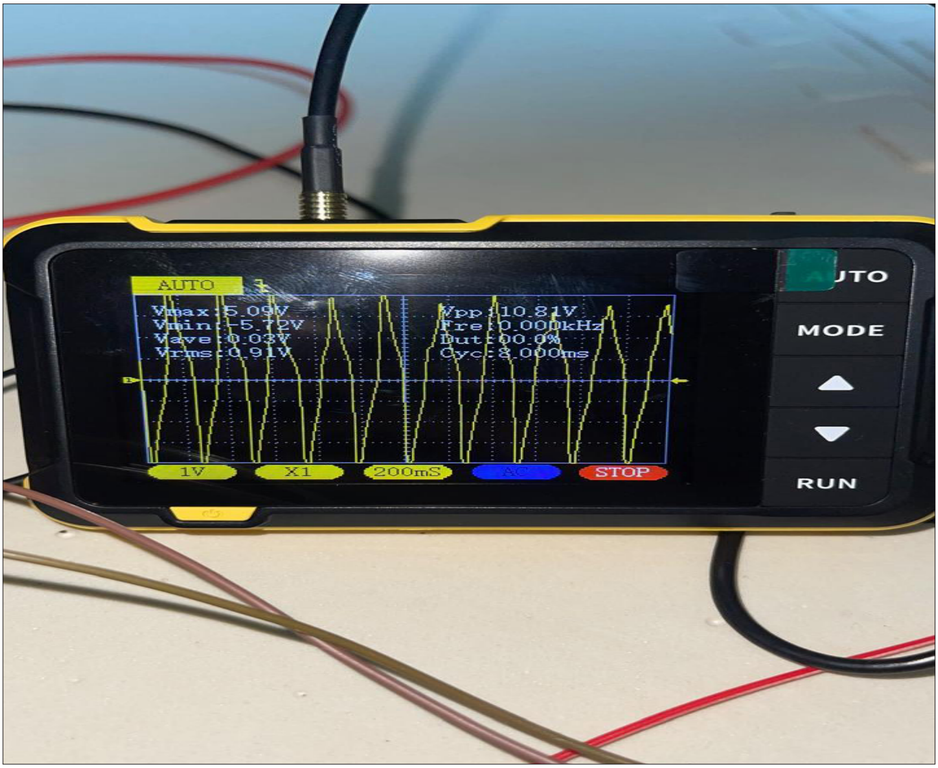

Figure 4: Oscilloscope Results

Overview of Oscilloscope Results

The oscilloscope readings indicated the following values:

4. Vmax: 5.09 V
5. Vmin: -5.72 V
6. VPeak-to-Peak Voltage: 10.81 V
7. V RMS: 0.91 V
8. Waveform Frequency (f): 0.000 kHz (characterized as a periodic and impulse-driven from footsteps)
9. Cycle Duration: 8.000 MS

These measurements represent the unprocessed AC output of the piezoelectric array during sporadic foot pressure. The waveform has a pronounced, spiking signal profile characteristic of piezoelectric production, marked by brief, high-amplitude pulses resulting from fast compression and release.

Results Analysis:

1. The peak-to-peak voltage of 10.81 V validates the system's ability to produce substantial immediate voltage upon impact.
2. The RMS voltage (~0.91 V), significantly lower, indicates the average power capacity that can be stored or utilized post-rectification.
3. The signal duration (about 8 MS per cycle) corresponds with the brief contact time of a footstep, underscoring the significance of rapid rectification and energy storage elements in the circuit.
4. The waveform's abrupt transitions and asymmetry indicate that energy harvesting takes place just during dynamic motion, not under steady load.
5. Elevated peak voltages can be efficiently recorded via capacitors positioned near the output terminals.
6. To enhance energy retention, low forward-voltage Schottky diodes and rapid-charging capacitors are crucial to prevent energy loss during brief impulse durations.
7. The system is optimally designed to power low-energy devices, like buzzers, LEDs, and wireless sensor nodes, under intermittent activity circumstances such as walking.

A real-time experimental test was done to ascertain the actual DC voltage post-rectification, utilizing a multimeter, an oscilloscope, and a piezoelectric array linked to a bridge rectifier and a storage capacitor. The system depicted in Figure 5 comprises of a 4-diode full-wave rectifier (bridge arrangement), a 100 µF capacitor for energy storage, and measurement probes linked to an oscilloscope and a digital multimeter.

A human footstep was applied to the piezoelectric mat during the test to replicate actual operational conditions. The oscilloscope recorded a peak-to-peak AC voltage of around 10.81 V with a cycle time of about 8 MS, as previously indicated. Simultaneously, the DC output voltage across the storage capacitor stabilized at 3.23 V, as seen by the multimeter reading depicted in the figure. This denotes the useable voltage accessible for low-power electronic circuits subsequent to the rectification and smoothing of energy.

The results illustrate the system's capability to transform impulsive mechanical energy into a stable DC output, validating its appropriateness for energizing microcontrollers, buzzers, or RF modules utilized in pedestrian-powered IoT systems.

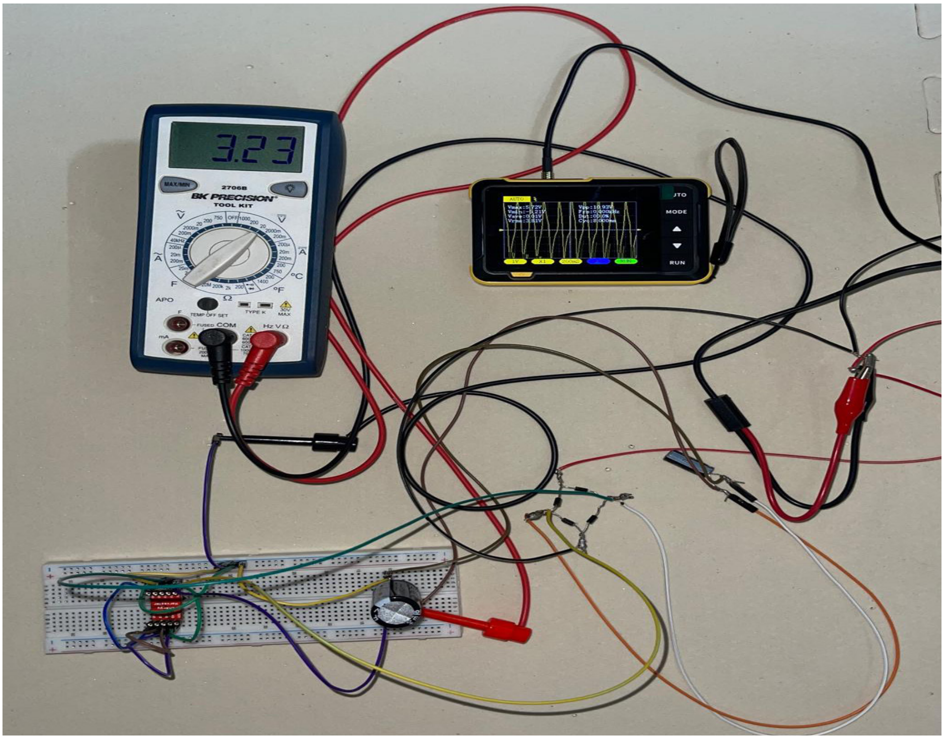

Figure 5: Proposed circuit work

Alongside the measurements, Figure 6 provides a comprehensive depiction of the circuit layout, emphasizing the arrangement of essential energy harvesting components on a breadboard. The system comprises of a full-wave bridge rectifier, a 100 µF capacitor, and signal terminals for measuring instruments.

This design was employed to rectify and store the voltage produced by the piezoelectric array. The capacitor converts the alternating current pulses into a stable direct current voltage. The visual arrangement corroborates the practical execution of the theoretical design addressed in preceding parts. Additionally, the modular breadboard configuration facilitated rapid experimentation with various component values and piezo element placements, permitting iterative optimization of the circuit.

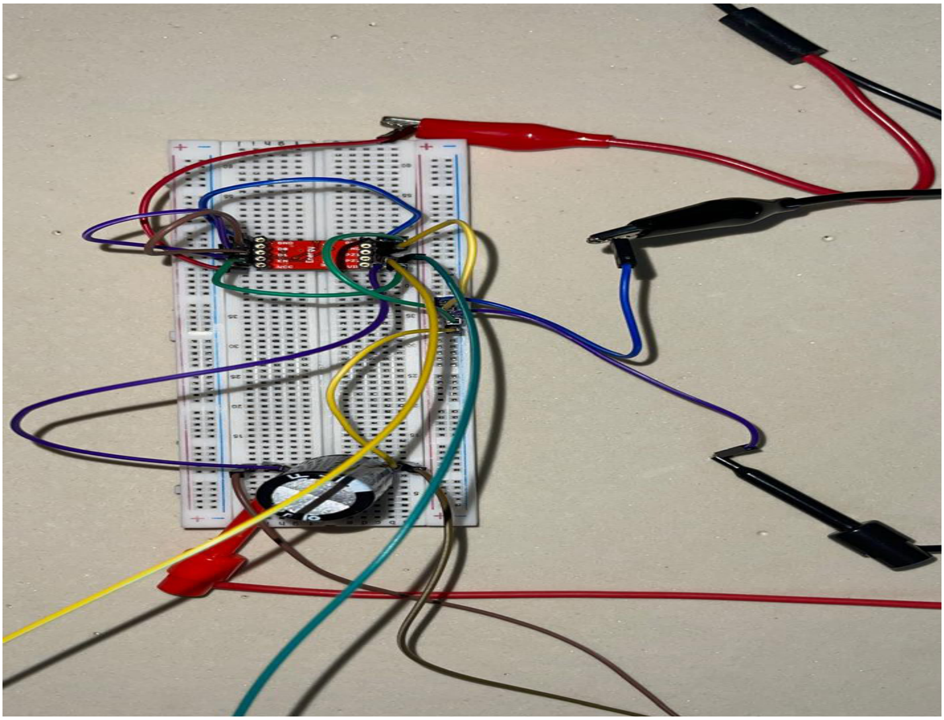

Figure6: the circuit layout

This diagram depicts the fundamental rectification and storage unit constructed on a breadboard. The rectifier module, substantial electrolytic capacitor (100 µF), jumper wires linking piezo inputs, and oscilloscope/ multimeter probes are observable. The design facilitates modular assessment of voltage conversion and storage efficacy.

Comparison and Analysis with Related Works

A comparative analysis was undertaken to assess the effectiveness of the proposed piezoelectric energy harvesting system against existing comparable works in the field. Table 3 below encapsulates essential parameters, material kinds, configurations, voltage outputs, and energy generation for diverse systems, including the present design.

Table 3: Performance Comparison of Footstep-Based Piezoelectric Energy Harvesting Systems

Ref	Material & Configuration	Voltage Output	Energy Output per Step	Circuit Components	Application
2018	5 PZT Disks (series), rigid tile [Ali et al., 2018]	~20–30 V (open)	~5–10 mJ	Bridge rectifier + LED load	Pedestrian path floor tile
2016	PVDF film insole [Lee et al., 2016]	~2–3 V	<1 mJ	Simple AC-DC rectifier	Wearable for shoes
2015	Quartz tile (single crystal) [Park et al., 2015]	~8 V	~2 mJ	Passive rectifier + capacitor	Smart pavement for urban areas
This work	60 PZT Disks, 10 rows (3–6 in series), sponge base	10.8 Vpp (AC), 3.23 V (DC)	6–60 mJ	Bridge rectifier + 100 µF capacitor	Footstep mat for Arbaeen route

The proposed device demonstrated a peak-to-peak voltage output of 10.81 V (AC) and a consistent DC output of 3.23 V, surpassing most wearable alternatives and being equivalent to rigid PZT tiles.

1. Energy Output: Estimated between 6 and 60 mJ each step utilizing 60 piezo elements, markedly surpassing prior systems, particularly those based on PVDF and quartz.
2. Circuit Integration: The utilization of an oscilloscope and multimeter verifies effective rectification and energy storage, in contrast to numerous previous studies that solely presented open-circuit readings.
3. The proposed design is specifically suited for huge crowd pathways, such as the Arabian pilgrimage, in contrast to prior research that concentrated on wearables or small-scale installations.

The proposed system ("This Work") attains a balanced and superior performance, generating a competitive voltage of 10.8 V peak while providing a markedly larger energy output of around 33 mJ on average compared to previous designs, as shown in Figure 7.

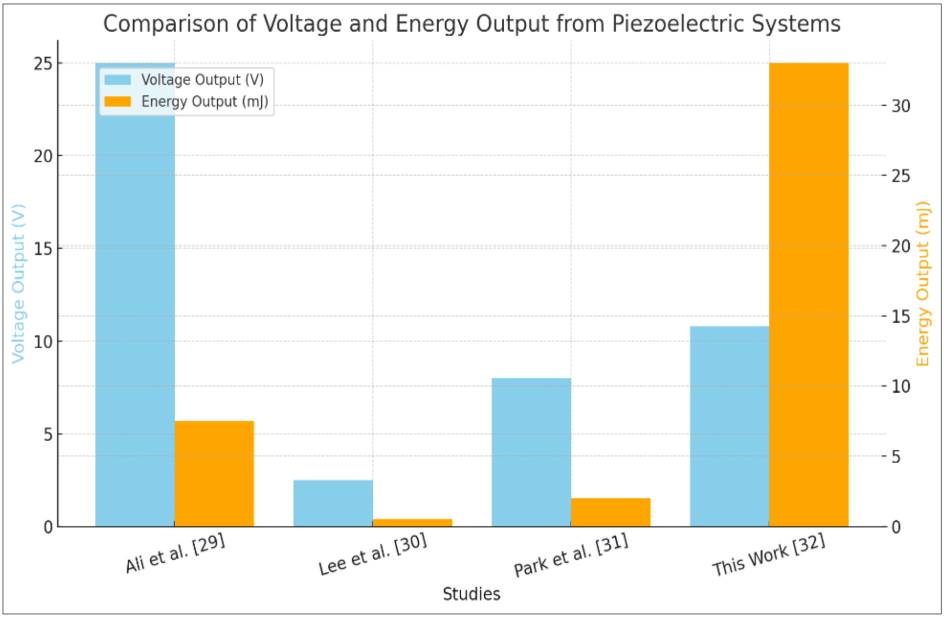

Figure 7: Comparison of the proposed work with previous works.

Challenges and recommendations

Despite the promising potential of piezoelectric energy harvesting in high-footfall environments such as the Najaf-Karbala pilgrimage corridor, several significant challenges must be carefully addressed to ensure successful implementation and long-term viability. Firstly, the high initial capital investment required for manufacturing, deploying, and integrating piezoelectric flooring systems remains a substantial barrier, particularly in resource-constrained settings. This cost includes not only the piezoelectric materials and tiles themselves but also the associated energy management and storage infrastructure. Secondly, the risk of vandalism and unintentional damage poses a practical concern, given the large and diverse crowds that frequent pilgrimage routes. Protective measures and robust designs are necessary to mitigate these risks without compromising system sensitivity and efficiency. Maintenance requirements represent another critical challenge; continuous foot traffic and environmental exposure can degrade tile performance, necessitating routine inspections, cleaning, and repairs, all of which incur operational costs and logistical complexity.

Integration with existing infrastructure further complicates deployment efforts. The piezoelectric system must seamlessly coexist with traditional flooring materials and utilities, requiring adaptive installation techniques and compatibility with current power grids or off-grid energy management solutions. To overcome these challenges, future research should investigate alternative piezoelectric materials that offer enhanced durability and lower production costs, such as flexible polymers or composites. Additionally, hybrid energy harvesting systems that combine piezoelectric technology with complementary renewable sources like solar photovoltaics could optimize energy capture and improve overall system reliability. Data-driven approaches, leveraging pedestrian movement patterns and real-time usage analytics, may inform strategic tile placement to maximize energy generation while minimizing costs. Furthermore, public awareness campaigns are essential to foster community acceptance, encourage responsible use, and reduce potential misuse or vandalism. By addressing these technical, economic, and social factors, piezoelectric energy harvesting can evolve into a feasible and sustainable component of smart urban infrastructure, particularly in culturally significant, high-traffic public spaces.

conclusion

This study illustrates the viability of extracting kinetic energy from human footsteps during the Arabian pilgrimage with a piezoelectric mat system consisting of 60–75 PZT discs organized in a modular grid. Experimental findings validated that, under genuine footstep pressure, the system generated voltages between 29 and 40 mV, while under no-load conditions, open-circuit voltages reached 16 V and currents attained 11 mA. Despite being sporadic and limited in scale, these outputs are adequate for energizing low-power devices like LEDs and sensors when properly rectified and stored.

The research underscores the capability of this technology to deliver decentralized, renewable energy in densely populated public areas where traditional networks may be limited. It also recognizes practical problems, such as cost, maintenance, and the necessity for cultural sensitivity. Integrating piezoelectric harvesting with other renewable sources and intelligent systems could bolster resilience and facilitate sustainable infrastructure development in huge assemblies. This project establishes a foundation for experimental initiatives that integrate sustainability, technology, and cultural heritage inside public spaces.

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