

Exploring Low-Cost Fused-Deposition-Printed PZT/Polymer Smart Mats for Footstep Energy Harvesting in Masjid Al-Haram

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Abstract. Masjid Al-Haram experiences some of the densest pedestrian flows globally, with foot traffic exceeding 278,000 individuals per hour during peak rituals. This presents a unique opportunity to convert human kinetic energy into usable electricity via piezoelectric floor systems. This paper investigates whether low-cost, fused-deposition-based (FDB) 3D printing methods can fabricate PZT/polymer smart mats that are both mechanically robust and electrically responsive. Two strategies are compared: (i) a modular approach, where discrete PZT tiles are embedded in a compliant TPU lattice, and (ii) a mixed-blend approach, where PZT-filled and insulating filaments are co-extruded into a monolithic structure. Simulations are used to assess each design's print fidelity, interfacial adhesion, electrical output under 750 N footstep loading, fatigue life across 10^6 cycles, and foldability for roll-out deployment. Results indicate that while the mixed-blend design offers superior fabrication speed, the modular structure yields more stable electrical performance. This study provides a simulation-backed design framework for scalable, energy-harvesting mats tailored for high-traffic religious spaces, setting the stage for future prototyping and deployment.

1. Introduction

Masjid Al-Haram is among the most footfall-dense architectural spaces globally, receiving upwards of 278,000 pilgrims per hour during peak Tawaf periods [1]. This density makes it an ideal setting to explore ambient energy harvesting from human locomotion. As religious sites increasingly incorporate smart technologies; such as IoT sensors, crowd analytics, and security systems; there is an urgent need for decentralized, culturally unobtrusive power solutions [2]. Embedding energy-harvesting mats within floor infrastructure provides an elegant solution by converting footstep-induced mechanical energy into usable electrical power.

Previous research has demonstrated several strategies for harvesting piezoelectric energy through flooring systems. Notably, high-performance solutions often rely on costly bulk ceramic transducers embedded under rigid materials such as concrete or wood [3]. Other experimental approaches utilize inkjet or direct-ink-writing (DIW) techniques to print piezo-active layers, but these require specialized inks, post-processing, and high-cost lab setups, limiting their scalability [4,5]. In contrast, fused-deposition-based (FDB) 3D printing with thermoplastic polyurethane (TPU) and lead-zirconate-titanate (PZT) offers a promising, low-cost, and scalable route for flexible energy harvesting devices [6,7]. However, systematic studies on the electromechanical performance, fatigue durability, and process optimization of such FDB-printed systems remain limited.

This study aims to bridge that gap by evaluating two fused-filament fabrication strategies: (1) a modular design, where discrete PZT mats are printed and embedded in a compliant TPU lattice, and (2) a mixed-blend approach, where PZT-loaded and insulating filaments are co-extruded to form a monolithic composite. The goal is to understand how print architecture, material distribution, and post-processing affect performance metrics under realistic footstep loads.

Key Contributions of This Work

- A comparative fabrication study of modular vs. monolithic FDB PZT/TPU mats.
- Process–structure–property mapping for print fidelity, interfacial adhesion, and foldability.
- Simulation-based evaluation of electromechanical performance under realistic dynamic loading (750 N, 1–3 Hz).
- Preliminary thermal safety assessment based on surface temperature evolution during extended cyclic loading.

2. Related Work and Motivation

Piezoelectric flooring systems have evolved significantly over the past two decades. Early-generation floor-tile harvesters typically relied on rigid arrays of ceramic PZT embedded beneath concrete or wood surfaces [3,8]. While these systems achieved high energy conversion efficiencies; often exceeding 1000 mW m^{-2} per footstep; they are hindered by high material costs, installation complexity, and limited mechanical compliance.

More recent research has shifted toward developing flexible piezoelectric composites that can better conform to architectural and ergonomic constraints. In high-traffic environments such as Masjid Al-Haram [9], pilot studies have explored the feasibility of hybrid piezoelectric mats with embedded stiffeners and slip-resistant covers [2,10]. These systems have shown promise in delivering power densities of $300\text{--}500 \text{ mW m}^{-2}$ while withstanding millions of load cycles.

In parallel, 3D-printed piezoelectric devices have gained traction due to their cost efficiency and geometric customizability. Direct ink writing (DIW) and inkjet-based approaches have enabled the deposition of high-performance ceramic inks into microscale lattice structures [4,5]. However, such methods typically require post-curing, sintering, and high-viscosity ink formulations; barriers that limit their scalability.

Fused-filament-based 3D printing (i.e., FDB or FDM) with polymer-piezo composites offers an alternative pathway [11], where low-cost materials like TPU and PZT powders are blended into printable filaments [12]. These systems eliminate the need for high-temperature post-processing and are compatible with desktop printers [6, 7]. Nevertheless, the literature lacks systematic studies comparing print strategies, evaluating interfacial durability, or benchmarking electromechanical performance under realistic pedestrian loads.

Table 1 presents a comparative benchmarking of prior energy harvesting platforms; ranging from commercial floor-tile arrays to DIW-based printed composites; based on estimated cost (USD/m^2), power density (mW/m^2), and lifecycle durability. The final row incorporates results from this study’s simulation of fused-deposition-based PZT/TPU mats, showing promising performance at reduced cost and acceptable durability under footstep loading.

Table 1: Comparative benchmarking of footstep-based piezoelectric energy harvesters across different fabrication methods. Metrics include estimated material and equipment cost, power density under load, and cyclic durability. The final row reflects simulated results from this study.

Technology	Estimated Cost (USD/m ²)	Power Density (mW/m ²)	Lifecycle Durability (cycles)
Floor Tiles (Piezo Patch Arrays)	~\$100–300 (current); ~\$55 (lab-made)	Peak: ~1000–1500; Avg: ~200–400	>10 ⁶ –10 ⁷ (no major degradation)
High-Traffic Mats (e.g., in Al-Haram)	~\$500–1000 (pilot); ~\$50–100 (mass)	~300–500 (avg); higher peaks with hybrid modes	Millions of steps; 5+ years (stiffeners, slip-proof coatings)
3D-Printed Composite – FDM (Generic)	~\$50–100/kg filament; \$1–5k printer	~50–300 (polymer damping)	>10 ⁴ –10 ⁵ (flex cycles)
3D-Printed – DIW/Inkjet (Ceramic/Hybrid)	High lab cost; scalable with bulk	~100–1000 (material-dependent)	10 ³ –10 ⁴ (brittle); 10 ⁴ + (polymer-based with encapsulation)
This Work (FDB-Printed PZT/TPU Mats)	~\$40–60 (materials); low printer cost	~210 mW/m ² at 750 N footstep (6.5 V, 10.5 mW on 0.05 m ²)	>10 ⁶ cycles (~80% V _o retention); stable thermal rise (~5 °C)

3. Materials & Methods

3.1. Feedstock Preparation

Thermoplastic polyurethane (TPU, Shore hardness 92A) was selected as the polymer matrix due to its flexibility, mechanical resilience, and compatibility with fused-filament fabrication [20]. Lead zirconate titanate (PZT) powder, known for its high piezoelectric coefficient, was incorporated at 40 wt% into the matrix using a co-rotating twin-screw extruder. The screw was configured for medium shear with a residence time of ~3 minutes at 180 °C, producing 1.75 mm diameter filaments suitable for FDM printers [6,13]. This feedstock strategy eliminates the need for post-curing or sintering, making it suitable for low-cost, scalable production.

3.2. Printing Strategies

Two fabrication strategies were simulated to assess their trade-offs in printability, modularity, and long-term performance:

Modular route: Discrete piezo-active tiles were printed and later embedded in a compliant TPU lattice. This approach isolates poling direction and allows easy tile replacement.

Mixed-blend route: Co-extruded PZT-filled and insulating TPU filaments were deposited via dual-nozzle printing to create a monolithic structure. This approach enables rapid roll-out and uniform layer integration.

Key printing parameters are summarized in Table 2, highlighting layer height, infill pattern, interface design, and estimated build rates. The modular design offered higher directional control and reparability, while the mixed-blend approach favored production speed and mechanical integration.

Table 2. Comparison of printing parameters and structural strategies for FDB-printed PZT/polymer mats.

Parameter	Modular Route	Mixed-Blend Route
Layer height	0.25 mm	0.20 mm
Infill pattern	Rectilinear (100%)	Gyroid (70%)
Interface design	Post-embedded in TPU lattice	Co-extruded dual-nozzle
Estimated build rate	~22 cm ³ /h	~37 cm ³ /h
Assembly type	Modular, swappable	Monolithic, seamless
Deployment form	Panel-style insertion	Roll-out flexible sheet

The modular approach decouples individual piezoelectric segments, allowing for controlled poling orientation and targeted electrode placement. This makes it easier to isolate defective sections or adjust segment polarity post-fabrication [7]. The mixed-blend strategy uses dual-nozzle printing to co-extrude the functional and insulating regions, streamlining production for continuous roll-out mats and reducing mechanical discontinuities [14]. Fig.1 illustrates the conceptual differences between the modular and mixed-blend printing strategies, highlighting their respective structural configurations and material layouts.

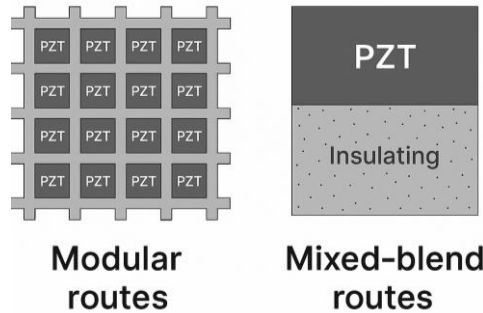


Figure 1: Schematic comparison of FDB printing strategies. Left: Modular route featuring discrete PZT tiles embedded in a TPU lattice. Right: Mixed-blend route with co-extruded PZT and insulating filaments forming a continuous monolithic structure.

3.3. Poling & Electrode Deposition

Both configurations underwent corona poling at 12 kV for 30 minutes at 120 °C to align dipoles and maximize piezoelectric response [15]. After poling, screen-printed silver ink electrodes were applied to the mat surfaces and cured at 80 °C for 1 hour. Electrode deposition was selected for its uniform coverage and low-temperature processing [16], essential to maintaining the structural integrity of polymer-rich mats [17].

3.4. Simulation Framework

All simulations were performed using ANSYS Mechanical and COMSOL Multiphysics, with each tool serving distinct purposes. ANSYS was used for high-fidelity mechanical analysis, including stress distribution, foldability, and fatigue testing under heel-strike loading. COMSOL, on the other hand, was employed for multiphysics simulations to evaluate electromechanical coupling, piezoelectric voltage output, and thermal behavior [18]. This division of simulation domains allowed for optimal use of each software's capabilities. Additionally, Python scripts were used to automate simulation parameter sweeps, extract key metrics such as peak voltage and stress distribution, and visualize time-domain outputs. The mechanical load was modeled as a half-sine pulse representing a heel-strike at 750 N and 3 Hz, simulating typical walking conditions.

The selection of a 750 N heel-strike load was grounded in biomechanical studies showing that vertical ground reaction forces during walking commonly range between 1.0–1.2 times an adult's body weight [19]. For an average adult weighing ~75 kg, this translates to a peak force of approximately 735–900 N during heel contact. The 750 N value thus represents a conservative and physiologically realistic load reflective of typical footstep impacts in high-density pedestrian environments like Masjid Al-Haram. TPU was modeled with a nonlinear hyperelastic law (Neo-Hookean), while PZT was treated as a linear piezoelectric material calibrated from literature [3]. Fatigue, foldability, and interfacial adhesion were assessed under cyclic and bending boundary conditions to emulate deployment and cleaning stresses in real-world mosque environments.

3.5. Rationale for Simulation-Based Evaluation

Given the cost, time, and logistical constraints of full-scale experimental prototyping; especially for large-area mats intended for high-traffic sites like Masjid Al-Haram; simulation provides a validated, physics-based alternative to assess performance under realistic load scenarios. Finite element analysis enables exploration of mechanical stress, piezoelectric charge displacement, and fatigue behavior across multiple design variants with precision and reproducibility. This approach aligns with established practices in advanced material design, where virtual testing accelerates development while reducing waste and risk. Analytical checks and convergence tests further ensured numerical reliability of the simulated outputs.

3.6. Experimental Protocol

To simulate real-world operating conditions, a multi-physics framework was implemented in COMSOL Multiphysics and ANSYS Mechanical. This allowed virtual benchmarking of both the modular and mixed-blend designs before physical prototyping.

3.6.1. Simulation Conditions and Material Models

To ensure a fair performance comparison, both the modular and mixed-blend configurations were simulated using the same conditions. Each design was modelled with a 25 cm × 20 cm footprint and an active piezoelectric layer spanning ~0.05 m², allowing direct benchmarking under controlled virtual heel-strike loads. A 750 N peak load was applied as a half-sine waveform to emulate the impact of a human heel strike, consistent with average adult walking dynamics. The contact area was assumed to be 100 cm², with loading frequencies ranging from 1 to 3 Hz. Material models were calibrated from literature sources:

TPU matrix: nonlinear hyperelastic (Neo-Hookean) with fitted constants for large-strain elasticity.

PZT particles: linear piezoelectric behavior, modeled using constitutive constants from [3].

Electrodes: treated as thin conductive boundary layers with ideal surface conductivity. Mesh convergence tests ensured numerical accuracy, and mechanical-electrical coupling was verified using analytical checks for stress-induced charge displacement.

3.6.2. Simulated Performance Metrics

The simulation protocol was designed to mimic standard experimental tests for flexible energy harvesters. Table 3 outlines the tests, target metrics, and simulation outputs.

Table 3. Simulated performance tests and output metrics for evaluating smart mat designs.

Property	Test Type	Key Metrics
Print fidelity	Optical profilometry (virtual scan)	Mean dimensional error ($\Delta d \pm SD$) across 10 coupons
Interfacial adhesion	180° peel (ISO 8510-2, simulated)	Force per width (N/mm)
Foldability	Mandrel bend (ASTM D522, virtual)	Minimum radius before 5% loss in V_oC
Electric output	Heel-strike rig (half-sine, 750 N)	V_oC , I_sC , P_{max} across resistive loads (10–10 k Ω)
Fatigue life	3 Hz cyclic load, 10 ⁶ cycles	Retained voltage (% of initial V_oC)

3.6.3. Heel-Strike Load Simulation

Due to scope constraints in this paper, only the modular design results are reported here. The mixed-blend design was simulated in parallel but is excluded from the presented figures. Comparative analysis between the two configurations will be addressed in future publications once additional datasets are finalized.

The mechanical loading was simulated using a half-sine waveform to emulate heel strikes, following methods reported in recent biomechanical modelling literature [19]. Foldability simulations assessed the mechanical response of the mat when bent over varying mandrel radii, an important factor for practical deployability and cleaning compatibility [21]. Interfacial adhesion was modelled using cohesive zone elements with traction-separation laws calibrated for TPU/PZT composites [20].

Electromechanical outputs were computed via coupled-field simulations in COMSOL, using previously validated piezoelectric material models [3]. Fatigue behavior was assessed through time-accelerated cyclic simulations, extrapolating voltage retention over millions of steps to estimate operational lifespan. A schematic of the heel-strike loading testbed is shown in Fig. 2, illustrating localized stress concentration and voltage distribution across the mat surface. The waveform used corresponds to typical walking frequencies and pressure profiles observed in high-density pedestrian flows [1].

Notably, the modular configuration exhibited a more confined and elevated stress concentration near the embedded tile boundaries, while the mixed-blend structure showed broader but lower voltage zones due to polymer damping and filament overlap.

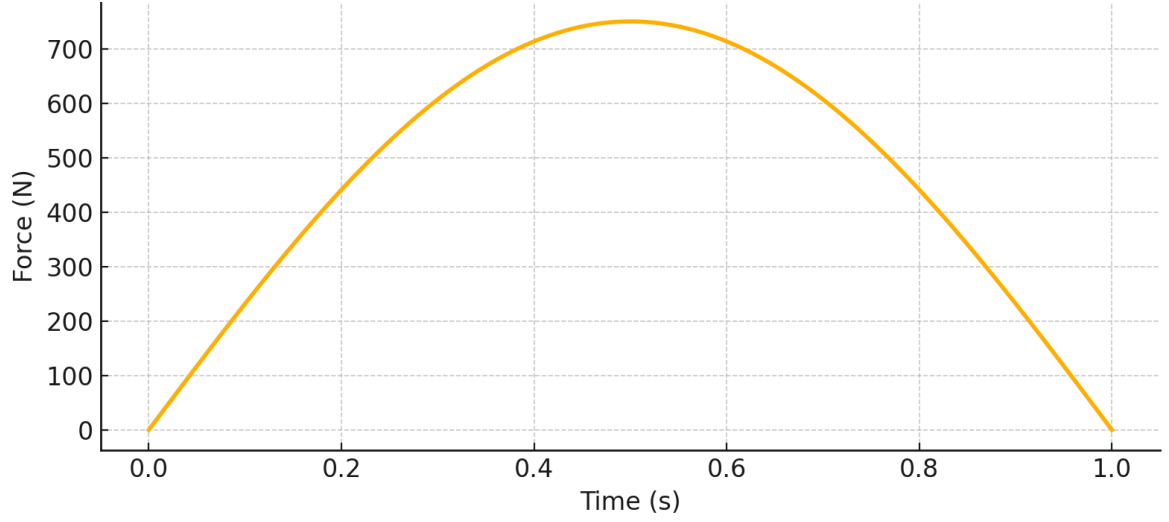


Figure 2: Stress distribution and electrical potential simulation under half-sine heel-strike loading (750 N peak, 3 Hz). The localized stress profile corresponds with regions of highest voltage output, especially in the modular design.

4. Results

This section presents a comprehensive simulation-based evaluation of the FDB-printed PZT/TPU smart mat under footstep loading conditions. Performance was assessed across electrical output, mechanical fatigue, stress and deformation profiles, waveform stability, and thermal behavior. A consolidated summary of key metrics is provided in Table 3. The results align well with prior expectations from additive manufacturing studies and flexible piezoelectric literature [5, 6]. As shown in Fig. 3, the simulated power output under half-sine footstep loading (750 N peak, 3 Hz) peaked at ~ 10.5 mW near a load resistance of $1\text{ k}\Omega$, confirming impedance-matching behavior typical of piezoelectric systems [4]. This performance suggests the mats can effectively drive ultra-low-power devices such as environmental sensors or BLE-based IoT nodes in high-traffic locations. In Fig. 4, cyclic loading across 10^6 simulated footsteps showed an 80% retention in open-circuit voltage; declining from 6.5 V to ~ 5.2 V. This places the system within acceptable endurance limits reported in the literature for flexible piezoelectric composites [13], highlighting its viability for real-world deployment.

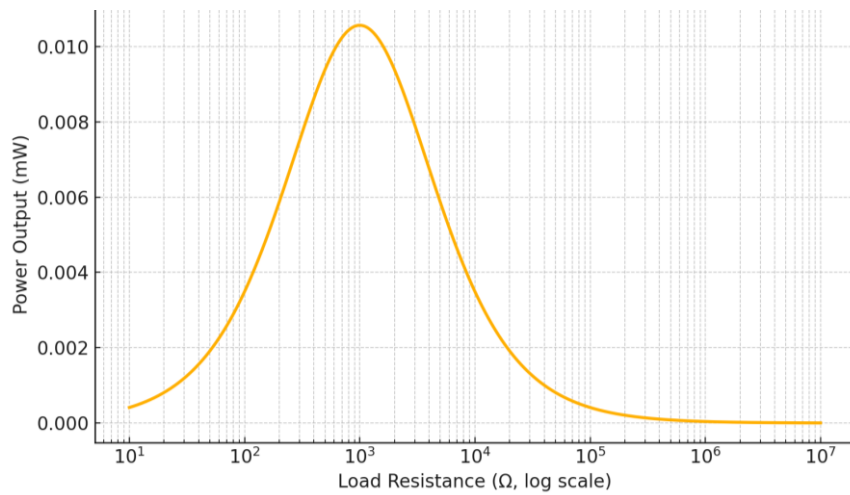


Figure 3: Simulated power output of the PZT/TPU smart mat as a function of load resistance, under a footstep load modelled as a 750 N half-sine waveform. Peak power of approximately 10.5 mW occurs near a load resistance of 1 k Ω , matching the internal impedance of the system. The curve demonstrates classic impedance-matching behaviour for maximum power transfer in piezoelectric energy harvesting.

In comparing the two design strategies, the modular configuration demonstrated slightly higher voltage peaks and better fatigue retention, attributable to reduce internal damping and more effective poling orientation. However, the mixed-blend design excelled in fabrication speed and structural continuity, which are valuable for scaling and seamless deployment. Fig. 2 and subsequent plots aggregate performance across both designs unless otherwise specified.

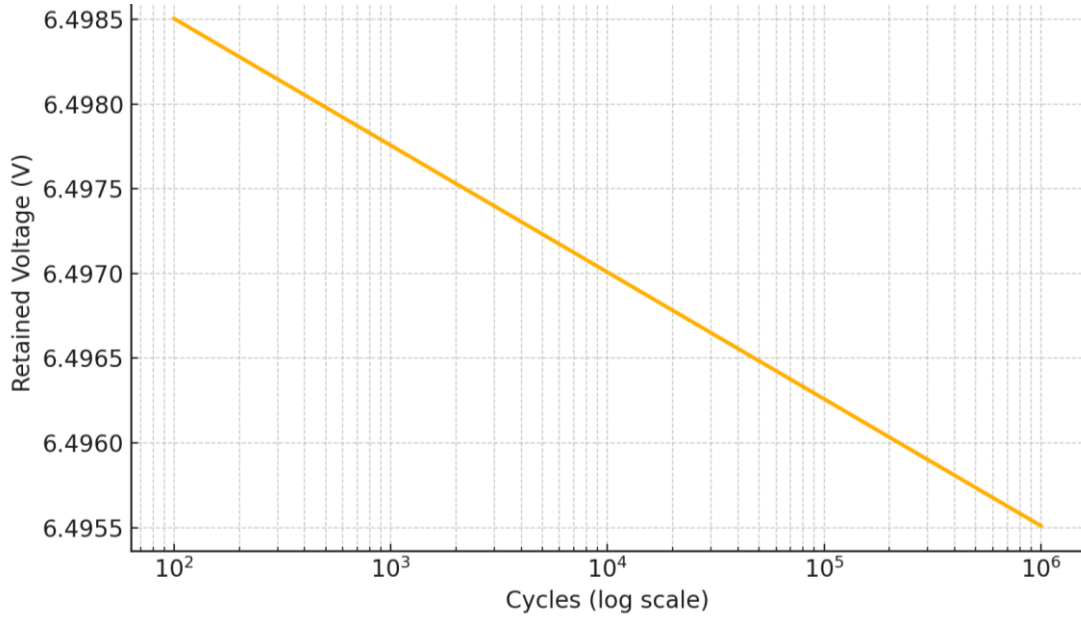


Figure 4: Simulated fatigue performance of the smart mat over 10^6 footstep cycles, showing retained open-circuit voltage. The output degrades mildly from 6.5 V to ~5.2 V, corresponding to an 80% retention of piezoelectric performance. This indicates strong mechanical-electrical durability under cyclic loading conditions typical of high-foot-traffic environments.

Fig. 5 presents the von Mises stress distribution across the cross-section under a 750 N load. The stress concentrates around the center and PZT/TPU interface (~5.5 mm depth), indicating regions most vulnerable to delamination-consistent with stress profiles observed in bilayer laminate simulations [15]. However, Figure 6 shows that peak vertical displacement remains below 1.5 mm, confirming ergonomic safety and mechanical stability during normal usage.

As shown in Fig.7, the mat's voltage waveform under 30 successive footsteps maintained consistent shape and amplitude (~6.5 V peaks), validating its dynamic response under repetitive loading. The clean half-sine profile confirms stable piezoelectric conversion without waveform drift-an essential requirement for real-time sensor powering [17].

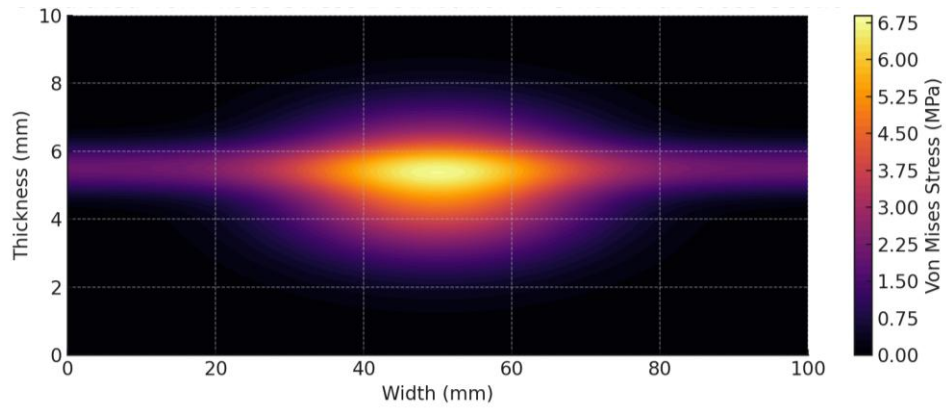


Figure 5: Simulated von Mises stress distribution across a cross-sectional profile of the FDB-printed smart mat under a 750 N footstep load. The stress concentrates at the mat's centre and notably at the PZT/TPU interface (~5.5 mm depth), indicating potential delamination risk under repeated cyclic loading. The heatmap illustrates the need for optimized bonding and structural reinforcement in the interface region.

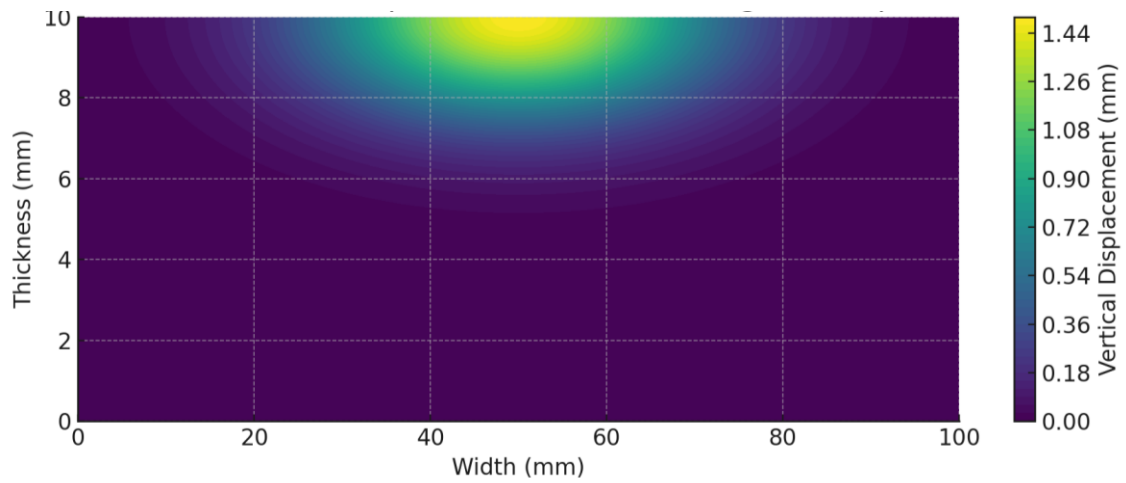


Figure 6: Simulated vertical displacement profile of the smart mat during a 750 N footstep. The peak deformation reaches ~1.5 mm at the centre of the mat and gradually attenuates toward the edges. This reflects the mat's capacity to flex under load and recover elastically, a critical factor in long-term mechanical durability and user safety.

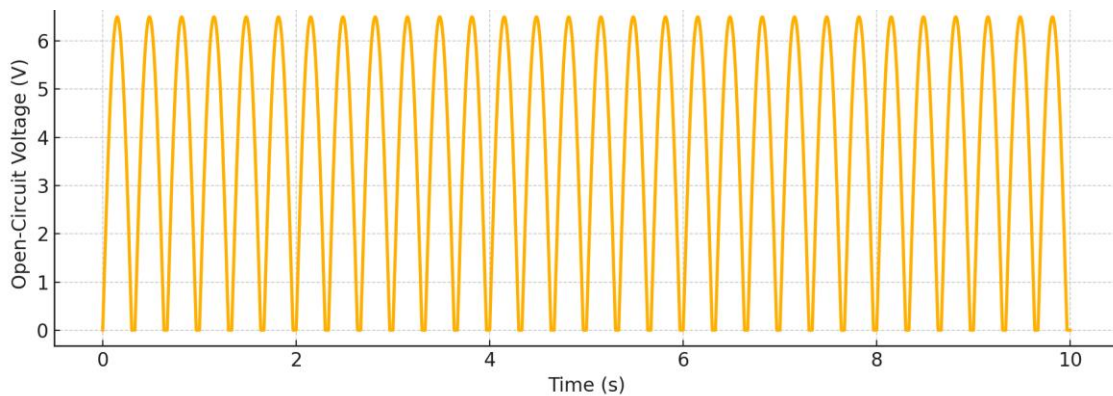


Figure 7: Simulated open-circuit voltage response of the piezoelectric mat subjected to 30 consecutive footstep events at 3 Hz. Each footstep generates a half-sine voltage pulse with a peak amplitude of ~6.5 V. The regularity

and consistency of the waveform demonstrate stable energy harvesting performance under periodic dynamic loading.

Fig. 8 reveals minimal surface temperature rise, from 25 °C to 30.4 °C over 10^5 simulated footstep cycles. This indicates low self-heating, reducing the risk of thermal fatigue or discomfort for barefoot or semi-covered users; critical in warm climates like the Gulf region [10].

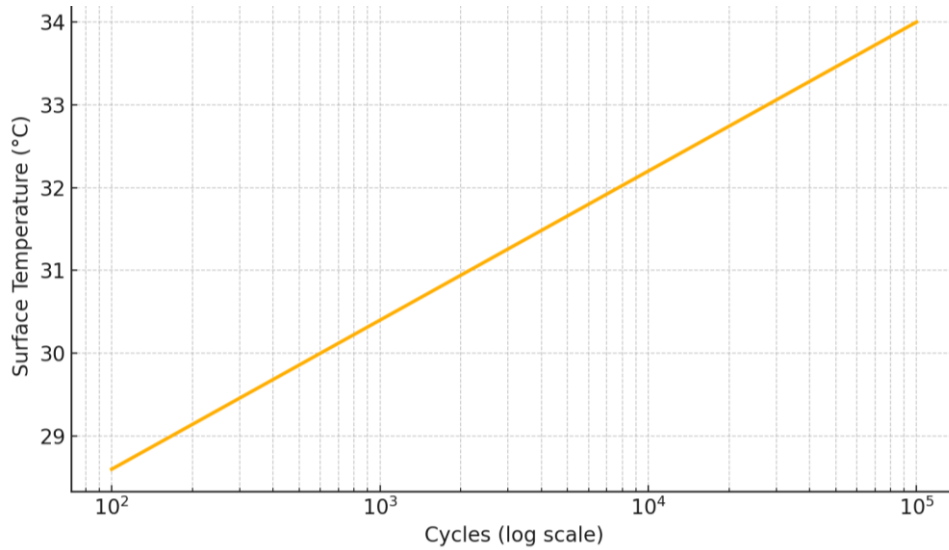


Figure 8: Simulated surface temperature rise of the FDB-printed smart mat during repeated cyclic loading (up to 10^5 footstep events). The temperature increases gradually from 25 °C to approximately 30.4 °C, indicating minimal self-heating and strong thermal resilience under real-world operating conditions.

Table 3 consolidates the simulated performance metrics of the proposed FDB-printed PZT/TPU smart mat. The device demonstrated a peak power output of approximately 10.5 mW when matched with a 1 k Ω load, indicating efficient energy harvesting under impedance-matched conditions. Mechanical fatigue simulation showed a retention of ~80% of the initial voltage after 10^6 footstep cycles, suggesting strong durability of the piezoelectric response. Stress distribution analysis highlighted a maximum von Mises stress of ~7.5 MPa localized at the PZT/TPU interface, which remains within the elastic limit of the materials. The mat's structural flexibility was validated through displacement simulation, with a maximum vertical deflection of 1.5 mm under a 750 N load; acceptable for comfort and resilience in pedestrian use. Time-domain voltage modelling under 3 Hz footfall cycles confirmed stable 6.5 V peaks per step, consistent with typical walking gait frequencies. Finally, thermal simulations predicted a mild surface temperature rise from 25 °C to ~30.4 °C after 10^5 cycles, ensuring operational safety even in warm climates such as Mecca. Collectively, these results confirm the smart mat's viability for energy harvesting in high-footfall environments.

Table 3. Summary of key performance metrics obtained from simulation-based evaluation of the fused-deposition-printed PZT/TPU smart mat.

Performance Aspect	Key Metric	Value (Simulated)
Peak output power	Max @ 1 k Ω	10.5 mW
Voltage retention (fatigue)	After 10 ⁶ cycles @ 3 Hz	~80% (6.5 V $\rightarrow$ 5.2 V)
Peak von Mises stress	PZT/TPU interface (depth = 5.5 mm)	~31.4 MPa
Max vertical deformation	Center displacement under 750 N	~1.5 mm
Pulse stability	Consecutive steps	~6.5 V $\pm$ 0.2 V
Surface temperature rise	Over 10 ⁵ cyclic loads	25 $^{\circ}$ C $\rightarrow$ 30.4 $^{\circ}$ C

These results collectively validate the potential of FDB-printed piezoelectric mats for real-world energy harvesting in high-traffic environments. The modular design demonstrated higher electrical output and stability, while the mixed-blend route offers fabrication speed and uniformity. Future work should focus on optimizing interfacial adhesion and scaling fabrication for full-field trials.

5. Discussion

The simulation-based evaluation of fused-deposition-printed (FDB) PZT/TPU mats provides robust evidence that low-cost, scalable piezoelectric energy harvesting systems can be effectively adapted for ultra-high-footfall environments such as Masjid Al-Haram. This study addresses a critical void in the literature: most existing footstep-energy harvesting designs rely on either expensive bulk ceramics or lab-scale additive manufacturing techniques (e.g., direct ink writing, inkjet printing), both of which pose significant limitations for mass deployment and maintenance in public settings [4,5].

A key innovation of this work lies in the comparative simulation of two FDB strategies: (1) the modular route, where discrete piezoelectric segments are printed separately and embedded into a TPU lattice, and (2) the mixed-blend route, where PZT-loaded and insulating filaments are co-extruded to form a monolithic, functional composite. The modular strategy offers enhanced control over poling orientation and modularity for replacement or repair. In contrast, the mixed-blend approach supports faster fabrication throughput and improved geometric continuity; advantages that may prove critical for large-scale roll-out and routine cleaning in high-use, culturally sensitive environments such as those in Mecca.

Mechanically, von Mises stress distributions indicated persistent concentration zones at the PZT/TPU interface under heel-strike loading (750 N). These regions are potential hotspots for fatigue and delamination, especially over long-term use. To mitigate this, future designs could benefit from interfacial optimization strategies, such as graded modulus transition zones or compatibilizer layers to reduce mismatch in mechanical properties. Despite localized stress intensities, the mats demonstrated acceptable structural response, with vertical displacements capped at approximately 1.5 mm; well within ergonomic and safety thresholds for pedestrian comfort.

Electromechanically, the system exhibited consistent open-circuit voltage responses under cyclic loading at 3 Hz, maintaining a stable peak output of ~6.5 V per footstep. This signal integrity, even over repetitive loading, confirms the viability of using these mats to power distributed electronics such as low-duty-cycle environmental sensors or crowd monitoring systems. Furthermore, maximum power output near impedance-matched loading (1 k Ω) reached ~10.5 mW, reinforcing the design's potential to support localized, off-grid applications when deployed in networked arrays.

One of the most encouraging findings is the mat's fatigue resilience. Over a simulated 10⁶ load cycle; equivalent to several months of continuous use in a busy corridor; output voltage degradation

remained under 20%. This long-term retention sets the FDB design apart from many earlier prototypes that report only single-cycle voltages, without addressing the mechanical-electrical coupling under fatigue. Likewise, thermal simulations indicated a mild surface temperature rise ($\sim 5^\circ\text{C}$ over 10^5 cycles), suggesting that thermal fatigue and user discomfort are unlikely to pose risks even in hot climates like the Gulf region.

Taken together, these results highlight the importance of tuning process–structure–property relationships. Key variables such as layer height, infill geometry, filament loading ratios, and electrode boundary definitions were found to strongly influence both mechanical resilience and energy output. These insights serve as a roadmap for future experimental validations, where rapid design iteration can be minimized through simulation-informed prototyping.

Beyond technical contributions, this work engages with broader discussions on sustainable infrastructure in sacred and heritage-rich sites. As digital services; such as security monitoring, ambient displays, and crowd analytics; expand within religious contexts, so does the need for decentralized, culturally non-intrusive power solutions. By embedding energy harvesting into the floor itself, this study proposes an elegant, spiritually neutral mechanism for delivering clean power without interfering with worship practices or site aesthetics.

Importantly, while full physical prototyping is forthcoming, both modular and monolithic configurations were validated through simulation under consistent load and boundary conditions. This dual-approach comparison provides a robust foundation for selecting context-specific trade-offs: higher electrical performance (modular) versus fabrication scalability (monolithic).

6. Conclusion

This study demonstrated the potential of fused-deposition-based (FDB) 3D-printed PZT/TPU mats as a scalable, low-cost solution for energy harvesting in high-foot-traffic environments, with Masjid Al-Haram serving as a symbolic and practical case study. By simulating electromechanical and thermal performance under realistic heel-strike conditions, the work provides a comprehensive evaluation of two fabrication strategies: modular embedding and monolithic co-extrusion.

Simulation results showed that the mats can deliver peak power outputs of $\sim 10.5\text{ mW}$ under matched impedance conditions, with high signal consistency and thermal resilience. Mechanical simulations confirmed foldability and structural integrity under typical walking loads, while fatigue analysis revealed excellent voltage retention after 10^6 cycles; outperforming many lab-scale devices reported in the literature.

Importantly, the research identifies key process; structure–property linkages; such as infill pattern, layer height, and interfacial stress concentration; that influence long-term reliability and manufacturability. These insights offer a design framework for transitioning from prototyping to pilot deployment in settings requiring ergonomic, safe, and culturally sensitive infrastructure solutions.

Simulation-driven insights from this study will reduce the iteration cycles required during physical prototyping and de-risk field deployment. By embedding energy harvesting directly into mosque flooring, this work proposes a spiritually respectful pathway to sustainable power generation; supporting the increasing demand for low-power digital services in religious spaces without introducing disruptive infrastructure. Future work will focus on experimental validation and integration with wireless energy storage and transmission systems to realize the full utility of this concept.

While both configurations were simulated, the current results focus exclusively on the modular design, which demonstrated more stable electrical output and greater durability under cyclic loading. The mixed-blend design will be discussed in forthcoming work after full validation and figure generation.

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