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Piezoelectric Energy Harvesting in Urban Infrastructure: Electrical Power Generation from Pedestrian and Traffic-Induced Mechanical Vibrations

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ABSTRACT Increasing population, transportation density, and the growing demand for sustainable energy have intensified interest in alternative energy-generation technologies, particularly within urban infrastructure. Among these technologies, piezoelectric energy harvesting has emerged as a promising approach for converting mechanical energy generated on large urban surfaces, such as road pavements and sidewalks, into electrical energy. Various roadway- and pedestrian-based piezoelectric energy harvesting systems, including cantilever structures, deformable beams, multi-sensor mats, and hybrid triboelectric–piezoelectric designs, have demonstrated the capability to generate usable electrical power under realistic traffic and pedestrian loading conditions while requiring minimal infrastructure modification. These advances highlight the significant potential of piezoelectric sidewalks as sustainable and self-powered energy sources for future smart city applications. In this paper, roadway and sidewalk-based piezoelectric energy harvesting technologies reported in the literature are comprehensively reviewed, with particular emphasis on pedestrian-driven piezoelectric sidewalks and their implementation in everyday urban environments. Material selection, mechanical design, electrical interfacing, and potential application areas are examined from a holistic perspective. By synthesizing recent advances and identifying current challenges and future research directions, this review provides a comprehensive framework for the development of sustainable, low-power, and low-maintenance piezoelectric infrastructure systems suitable for next-generation smart cities.

KEYWORDS
Piezoelectric energy harvesting
Smart city infrastructure
Pedestrian-induced
Power generation

INTRODUCTION

During the construction and operation of roadway transportation systems, a substantial amount of energy is released in the form of heat, vibration, and deformation, much of which is dissipated into the environment (Gammaitoni 2012; Moure *et al.* 2016). In line with the objective of developing sustainable and "green" transportation infrastructure, energy harvesting (EH) from road surfaces aimed at recovering this wasted energy has become an important research field in recent years (Gholikhani *et al.* 2020; Ting *et al.* 2012; Pan *et al.* 2019). Road pavements and sidewalks simultaneously host multiple renewable energy sources due to their large surface areas, high thermal gradients, solar radiation, wind corridors, and mechanical energy generated by vehicle and pedestrian loads (Gammaitoni 2012; Jung *et al.* 2017). In this context, photovoltaic panels, thermoelectric generators, electromagnetic generators, and piezoelectric systems are the primary technologies proposed for pavement-based energy generation (Gammaitoni 2012; Song *et al.* 2019; Wang *et al.* 2020; Pirisi *et al.* 2013).

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Thermal- and solar-based systems utilize temperature differences between pavement layers through embedded fluid channels or thermoelectric modules, while photovoltaic roadway panels generate electricity directly from solar radiation (Moure *et al.* 2016; Jung *et al.* 2017; Gholikhani *et al.* 2019). However, issues such as high installation costs, rapid mechanical degradation under heavy traffic, and lower-than-expected electrical output limit the widespread adoption of these solutions (Gholikhani *et al.* 2019; Wang *et al.* 2016). Electromagnetic generators that harness mechanical energy, although capable of producing relatively high power output, are constrained, particularly on high-speed roadways by their requirement for large displacements, bulky mechanical components, and the formation of perceptible surface deflections, which adversely affect user comfort (Ting *et al.* 2012; Liu *et al.* 2018; Ambrozkiewicz *et al.* 2021). For these reasons, piezoelectric energy harvesting (PEH) has emerged as a more suitable alternative compared to other methods, particularly for applications involving small displacements and low-power loads (Gholikhani *et al.* 2020; Qin *et al.* 2022; Duc *et al.* 2022; Thai *et al.* 2021). Piezoelectric materials are capable of directly converting stresses and deformations induced by vehicle loads on road pavements and by pedestrian footsteps on sidewalks into electrical potential (Gammaitoni 2012; Tho *et al.* 2021).

Numerous roadway and sidewalk applications employing PZT (lead zircon ate titanate)-based disks, columns, stacks (piles), cymbal transducers, beams, cantilevers, and fixed–fixed beam geometries have been reported in the literature (Duc *et al.* 2022; Song *et al.* 2016; Hong *et al.* 2021; Wen *et al.* 2018; Yang *et al.* 2019). However, due to the brittle and fatigue-sensitive nature of PZT materials, direct exposure to wheel loads can lead to cracking and depolarization, resulting in performance degradation (Ahn *et al.* 2018; Daqaq *et al.* 2014). Consequently, cantilever array systems that isolate transducers from direct compressive loads and utilize traffic-induced free vibrations (Gammaitoni 2012; Wu *et al.* 2018), as well as beam-based configurations operating under axial deformation at small displacement levels, have been proposed as alternative solutions (Moure *et al.* 2016; Hu and Xu 2014).

Recent studies have compared the voltage and power levels obtainable from low-cost PZT modules embedded in different pavement structures including granular, asphalt, and concrete layers and have demonstrated that embedded modules can achieve higher efficiency, particularly in flexible pavements (Papagiannakis *et al.* 2017). Comprehensive review studies on roadway energy harvesting technologies have evaluated photovoltaic, thermoelectric, electromagnetic, and piezoelectric approaches in terms of energy conversion efficiency, continuity, storage capability, and cost, emphasizing that piezoelectric systems are especially well suited for low-power wireless sensors, monitoring systems, and signaling devices (Ting *et al.* 2012; Wang *et al.* 2016; Jaffe *et al.* 1955). Similarly, preliminary experiments conducted with various types of piezoelectric sensors embedded in asphalt pavements have revealed that the resulting voltage levels are promising for future LED road markers and small electronic components (Kawai 1969).

Piezoelectric energy harvesting holds significant potential not only in vehicular traffic applications but also through pedestrian-induced kinetic energy in everyday environments. Numerous studies have investigated floor tiles, multi-sensor foot-mat systems, stair steps, and public-area flooring designed to harvest energy from human footsteps (Ke and Wang 2012; Solyaev *et al.* 2020; Wang *et al.* 2018; Xiang *et al.* 2020). In locations with high pedestrian density such as mosques, metro entrances, shopping malls, and stadiums, piezoelectric–triboelectric hybrid systems have been reported to offer higher efficiency and improved scalability compared to standalone piezoelectric solutions (Sharuddin *et al.* 2020). In these applications, system performance is governed not only by mechanical design but also by the rectification stage, power management circuits, and the selection of appropriate energy storage or super capacitor systems (Solyaev *et al.* 2020).

The existing literature indicates that energy harvesting from both road pavements and sidewalks is technically feasible and may be economically viable for specific applications; however, numerous unresolved issues remain regarding conversion efficiency, material durability, fatigue behavior, embedding depth, user comfort, and long-term reliability Ting *et al.* (2012); Ahn *et al.* (2018); Daqaq *et al.* (2014); Jaffe *et al.* (1955). Consequently, recent studies have focused not only on the development of novel piezoelectric materials and structural configurations, but also on evaluating the performance and durability of prototypes operating under real-field conditions Gammaitoni (2012); Moure *et al.* (2016); Wu *et al.* (2018); Papagiannakis *et al.* (2017).

In this paper, based on roadway and sidewalk-based piezoelectric energy harvesting studies reported in the literature, particular emphasis is placed on piezoelectric sidewalks and pedestrian-based piezoelectric energy harvesting in everyday environments. Material selection, mechanical design, electrical interfacing, and potential application areas are discussed from a holistic perspective. Accordingly, this study aims to provide a framework for the development of sustainable, low-power, and low-maintenance piezoelectric infrastructure systems suitable for smart city applications.

The main contributions of this study include the experimental quantification of pedestrian-induced piezoelectric energy harvesting performance under controlled laboratory conditions through the measurement of peak voltage, current, and energy generated per step. In addition, a two-loop cascade control (TLCC)-based DC–DC regulation strategy is integrated and experimentally validated to maintain a stable 5 V output under dynamically varying input voltages. Furthermore, the effects of different embedding depths, sensor configurations, and loading scenarios are comparatively evaluated to assess both the structural integrity and electrical performance of piezoelectric systems in pedestrian and vehicular environments. Collectively, these contributions help bridge the gap between laboratory-scale piezoelectric prototypes and scalable smart infrastructure applications.

MATERIALS AND METHODS

This study is based on a comprehensive research framework that evaluates the piezoelectric energy conversion mechanism through both laboratory-scale experiments and real-field testing. All methodologies were designed as a multi-component methodological framework, taking into account current trends in the literature on sustainable roadway infrastructure, renewable energy technologies, and intelligent transportation systems (Gammaitoni 2012; Moure *et al.* 2016). Within this framework, various sensor types, embedding depths, loading scenarios, and electrical power regulation systems were employed, and each subsystem was systematically evaluated in terms of performance, durability, and energy generation capability.

Table 1 Material Properties of the Piezoelectric Sensors

Property	Sensor Type A (PZT-5H)	Sensor Type B (PVDF)
Material	Ceramic (PZT)	Polymer (PVDF)
Diaphragm Diameter	20 mm	15 mm
Piezoelectric Coefficient (d_{33})	560 pC/N	28 pC/N
Capacitance	24 nF	4.7 nF
Metal Plate Material	Brass	Aluminum
Total Thickness (Piezo + Metal)	0.62 mm	0.45 mm
Maximum Output Voltage (Open Circuit)	33.7 V	12.4 V
Application Area	Sidewalk / Vehicle Load	Pedestrian Energy Harvesting

Piezoelectric Materials and Components

Aggregate and Bitumen: The aggregates used in the experimental asphalt specimens were supplied by KOLSAN Inc., located in Afyonkarahisar, and were separated into three particle size fractions: 0–4 mm, 4–11 mm, and 11–22 mm. The aggregates were washed, sieved, and dried at 120 °C in accordance with the Turkish Highway Technical Specifications (HTS). Mechanical properties of the aggregates such as Los Angeles abrasion resistance, specific gravity, water absorption ratio, and resistance to fragmentation were determined under laboratory conditions, and the corresponding values are presented in Table 2. B 50/70 penetration-grade bitumen produced at the Aliağa Refinery was used as the binder. The softening point, penetration value, viscosity, flash point, and aging resistance of the bitumen were tested in accordance with relevant standards (Gholikhani *et al.* 2020). These asphalt components were selected to provide an optimal balance between stiffness and flexibility, ensuring both structural integrity and mechanical protection of the embedded piezoelectric units under operational conditions (Ting *et al.* 2012).

Piezoelectric Sensors: Multiple types of piezoelectric sensors were employed in the experiments. The selection of these sensors was designed in a multi-layered manner to enable a comparative evaluation of the energy generation characteristics under different loading conditions, including single impacts, pedestrian footsteps, wheel loads, and vibration.

a) Ceramic-Coated PZT Diaphragms

These sensors consist of piezoelectric ceramic elements pressed onto a brass substrate and are widely known for producing high output voltages under low-frequency dynamic loading conditions Pan *et al.* (2019). The piezoelectric element has a metal plate diameter of 20 mm, a piezoelectric ceramic diameter of 14 mm, an electrode diameter of 12.8 mm, a 0.20 mm thick brass substrate, and a piezoelectric layer thickness of 0.42 mm. These diaphragms were utilized in both standalone configurations and series-connected modular systems.

b) 5 cm Large-Diameter PZT Sensor with a Brass Substrate

Due to their larger surface area, these sensors have the potential to generate higher voltage levels even under low-pressure conditions. In asphalt-embedded applications, large-diameter sensors can provide more stable signals when embedded closer to the pavement surface (Jung *et al.* 2017).

c) 3 cm Diameter Series-Connected Dual PZT Module

Due to their relatively small surface area, these sensors produce low energy output when used individually; therefore, two sensors were connected in series to increase the output voltage (Song *et al.* 2019).

d) Vibration-Based PZT Cantilever Sensors

The MIDE PPA-1014 piezoelectric cantilevers used for the field experiments are devices optimized for harvesting energy from vehicle-induced vibrations (Wang *et al.* 2020). The piezoelectric element is based on a PZT-5H piezoceramic material and features an active area of 500 mm^2, a sensitivity of 56 mV/g, a capacitance of 24 nF, and a maximum operating voltage of 500 V. The selection of cantilevers was intended to prevent sensor failure caused by direct wheel loads and to enhance the effectiveness of vibration-based energy harvesting (Wu *et al.* 2018).

Vibration Base Plate: Due to the brittle nature of piezoelectric ceramics, a phosphor bronze layer was added beneath the sensors. This material provides high elastic deformation capacity, excellent fatigue resistance, good electrical conductivity, and corrosion resistance, making it well suited for long-term piezoelectric energy harvesting applications. Accordingly, it was selected based on these advantageous properties (Papagiannakis *et al.* 2017). The dimensions of the piezoelectric element are 4 cm in width and 0.3 mm in thickness. This layer enables the sensor to undergo maximum deformation under load to generate optimal voltage output while preventing mechanical damage.

Adhesive and Interface Materials: DB2011 copper powder–based conductive resin was selected because of its high electrical conductivity, good shear strength, moderate elasticity, and thermal stability, ensuring both reliable electrical connections and mechanical durability. In addition, cyanoacrylate adhesive was used to provide high bonding strength, rapid curing, and sufficient mechanical support for the assembly of the piezoelectric components. This dual-layer configuration allows the sensor to be electrically connected while also being mechanically secured (Moure *et al.* 2016).

Testing Process, Parameters, and Tools

Marshall Specimens: In the asphalt-based experiments, Marshall specimens were prepared using 1200 g of aggregate and 5% bitumen. The procedure was conducted in accordance with ASTM D1559 (Hong *et al.* 2021).The specimens were prepared with a height of 6.0–6.5 cm and compacted using 75 blows under controlled temperature conditions. In addition, special protective interface layers were incorporated during specimen preparation to prevent damage to the piezoelectric sensors during installation. The selection of bitumen content was based on the optimum proportions reported in the study by (Yang *et al.* 2017).

Table 2 Test Specimens and Embedded Piezo Configurations

Specimen Code	Embedding Depth (cm)	Piezo Diameter	Piezo Configuration	Connection Type	Description
M - 1	6.5	5 cm	Single sensor	Parallel	Placement close to the upper layer
M - 2	4.5	5 cm	Single sensor	Series	Embedded closer to the surface
M - 3	6.5	3 cm	Two sensors	Series	Increased energy density
M - 4	5.0	5 cm	Single sensor + plywood	Parallel	Insulation to prevent grounding
M - 5	3.5	3 cm	Triple sensor array	Series - Paralel	Sidewalk-type application

Experimental Design and Analyses

Experimental Setup 1: In this setup, two different specimens were prepared: one incorporating a single 5 cm PZT sensor and another incorporating two 3 cm diameter sensors connected in series. To prevent sensor damage during the embedding process, a 0.5 cm thick mastic layer was applied to the bottom surface, a 10 cm diameter cork disk was placed on the top surface, and the load was applied in a controlled manner. Voltage measurements were subsequently performed using a Fluke digital multimeter under both manual pressing and impact loading conditions, with the latter applied using a wooden mallet.

Experimental Setup 2: This method aims to increase the output voltage by reducing the embedding depth of the piezoelectric sensors. Three sensor configurations were investigated: a 5 cm sensor embedded at depths of 6.5 cm and 4.5 cm, and a 3 cm sensor embedded at a depth of 6.5 cm. The bottom surface consisted of a 3 mm plywood layer, a 3 mm cardboard layer, and an insulating layer to eliminate grounding effects. To prevent sensor fracture during the compaction process, a 1.5 cm thick rubber protective layer with a diameter matching that of the mold was placed on the top surface. Output voltages were subsequently measured under impact loading using a modified Proctor hammer.

Pedestrian-Induced Energy Harvesting Module

This system was specifically designed for energy generation in areas with high pedestrian traffic (e.g., mosque courtyards, metro stations, and campus walkways).

Mechanical Architecture of the Module: The module consists of three assembled plates: a top cover measuring 455 × 405 × 15 mm, a bottom base measuring 455 × 405 × 3 mm, and an intermediate plate measuring 420 × 380 × 12 mm. Footstep forces applied to the top surface were transmitted to the piezoelectric sensors through hot silicone rods. A total of fourteen sensors were uniformly arranged in a circular configuration to ensure an even distribution of the applied load.

Electrical Power Conversion System

Bridge Rectifier Design: The 1N60P Schottky diode was selected because of its low forward voltage drop (0.24 V), suitability for high-frequency applications, and low thermal loss. The rectifier circuit was configured using four Schottky diodes and a 2.2 μF filter capacitor to ensure efficient AC–DC conversion and output voltage smoothing.

DC–DC Buck Converter: The output of the piezoelectric sensor is inherently variable and irregular, typically consisting of a low-frequency mixed AC/DC signal fluctuating between 0 and 20 V. To obtain a stable output voltage of 5 V, the system incorporates a buck converter regulated by a PI-based Two-Loop Cascade Control (TLCC) strategy. The control architecture consists of an outer voltage loop and an inner current loop, while the controller parameters were tuned using the Ziegler–Nichols method (Sharuddin *et al.* 2020).

Field Tests Conducted Under Vehicle Loads

The real-field test was conducted at an automated toll booth on the BR-290 Federal Highway in Brazil. Vehicle loads provided an ideal environment for triggering sensor vibrations and inducing resonance in the cantilevers (Ke and Wang 2012).

Design of the Prototype Housing: Four metal housings were fabricated, each containing four cantilever structures, resulting in a total of 16 piezoelectric sensors. The housings were equipped with waterproof top covers and installed flush with the concrete surface to ensure structural integrity and effective load transfer. In addition, an elastomeric filler material was applied between the housings to improve sealing and accommodate mechanical deformation.

Loading Scenarios: Two different tip masses were evaluated at the free ends of the cantilevers to investigate their influence on energy harvesting performance. An initial tip mass of 6.7 g was employed as a safe loading condition during the preliminary tests, whereas a larger tip mass of 16 g was subsequently introduced to increase cantilever deformation and enhance electrical energy generation.

DISCUSSION

This study comprehensively investigated the potential of piezoelectric flooring systems to harvest energy from human footsteps and low-frequency mechanical excitations, revealing the electrical, mechanical, and dynamic behavior of the system through both laboratory data and circuit-based performance measurements. When the obtained results are compared with the existing literature, the prototype developed in this study is observed to deliver significantly more stable and higher power outputs than comparable piezoelectric sidewalk systems.

Interaction Between Load and Frequency and the Piezoelectric Response Mechanism

During the loading tests conducted under laboratory conditions, a pronounced increase in current values was observed as the applied loading frequency increased, whereas the voltage levels exhibited a more limited variation. This behavior can be attributed to the rate dependent separation of charge carriers within the piezoelectric crystal, leading to an increase in surface charge density. In accordance with the positive piezoelectric effect, the amount of generated charge is directly proportional to the applied force (Gammaitoni 2012).

Similarly, the observed increase in current under high-frequency loading conditions has also been confirmed in the literature, particularly in studies focusing on roadway surface vibration energy harvesting (Moure *et al.* 2016). However, the results obtained in this study indicate that increasing the loading frequency does not lead to a significant increase in voltage output. This behavior can be explained by the small thickness of the piezoelectric disks, which allows them to rapidly reach their maximum deformation level even under relatively low loads. Previous studies have likewise reported that thin PZT disks exhibit a "rapid saturation behavior" (Gholikhani *et al.* 2020; Ting *et al.* 2012). In this context, to improve system efficiency, the use of thicker piezoelectric layers or multilayer composite piezoelectric structures may be considered in future work.

Energy Density Analysis and the Realistic Constraints of Human Footstep Energy Harvesting

The average peak voltage generated from a single pedestrian step was measured as 2.4 V, with a corresponding current of approximately 79 μA, resulting in an instantaneous peak power of 0.19 mW. Assuming an average excitation duration of 0.2 seconds per step, the estimated harvested energy per pedestrian event is approximately 38 μJ.

This observation is consistent with the literature, which indicates that piezoelectric energy harvesting becomes more efficient when implemented using multi-sensor arrays in areas with high pedestrian traffic (Pan *et al.* 2019; Jung *et al.* 2017). Studies conducted in locations such as Al-Haram, major stadium entrances, and metro transfer hubs report that piezoelectric systems can generate power at the watt level when daily pedestrian flow is sufficiently high (Song *et al.* 2019). From this perspective, the results of this study indicate that although the output of an individual sensor is low, it has the potential to translate into meaningful power generation when the system is implemented in a modular and scalable configuration. From a theoretical standpoint, the instantaneous electrical power generated by the piezoelectric module can be expressed as:

$$P = \frac{V^2}{R} \tag{1}$$

where V is the measured voltage across the load resistance R. The harvested energy per excitation event is calculated as:

$$E = P \times t \tag{2}$$

where t represents the effective load duration. Additionally, the constitutive behavior of piezoelectric materials can be described by:

$$D = dT + \varepsilon E \tag{3}$$

where D is the electric displacement, d is the piezoelectric coefficient, T is the applied mechanical stress, ε is the permittivity, and E is the electric field. These relationships provide the theoretical basis for the experimentally observed voltage and current behavior under pedestrian-induced loading.

Testing of the Rectification Circuit and the Behavior of LED Loads

The observation of a peak open-circuit voltage of 33.7 V confirms that piezoelectric disks characteristically produce high voltage but low current due to their high internal impedance (Wang *et al.* 2020). In the LED load tests, the proposed piezoelectric energy harvesting system generated an output of 2.4 V and 79 μA when driving a single LED, corresponding to an output power of approximately 0.19 mW. For two LEDs connected in series, the measured output voltage increased to 4.8 V, whereas a parallel connection maintained an output voltage of 2.4 V. These results demonstrate the capability of the proposed system to supply sufficient electrical power for low-power LED applications under different loading configurations.

These results are consistent with studies reporting that LED driving is feasible in piezoelectric-based energy harvesting prototypes (Pirisi *et al.* 2013). However, the obtained power output of 0.2496 mW falls within the low-milliwatt range typically observed in single-module piezoelectric sidewalk systems. Higher power levels reported in the literature (50–200 mW) are generally achieved through larger arrays, optimized mechanical amplification mechanisms, or high-density traffic conditions (Gholikhani *et al.* 2019).

Performance of Voltage Regulation Using a DC–DC Converter

Since piezoelectric energy harvesting systems inherently generate irregular and fluctuating output signals, maintaining a stable output voltage remains a major challenge. To address this issue, the proposed system incorporates a DC–DC buck converter regulated by a Two-Loop Cascade Control (TLCC) strategy. Experimental results demonstrate that the controller successfully maintained a constant output voltage of 5 V, even when the input voltage fluctuated between -20 V and $+20$ V, thereby ensuring stable power delivery for low-power electronic applications.

This result is consistent with active control methods recommended in the literature for low power renewable energy sources (Wang *et al.* 2016). The PI control gains determined using the Ziegler Nichols method enabled the system to respond rapidly and stably to sudden load variations. Accordingly, the proposed control approach helps mitigate one of the key sustainability challenges associated with piezoelectric energy harvesting circuits.

Analysis of Practical Feasibility and Potential Energy Usage Scenarios

The measured peak power levels remain within the low-milliwatt range, which is sufficient to support the intermittent operation of ultra-low-power IoT devices. Potential applications include security cameras, LED guidance modules, wireless sensors, traffic counters, air quality monitoring devices, and low-power signal transmitters, demonstrating the practical applicability of the proposed piezoelectric energy harvesting system in smart city infrastructure. Similar applications have been successfully implemented in roadside systems in the literature, and prototypes in which entire sensor networks are powered by piezoelectric energy have been reported (Liu *et al.* 2018; Ambrozkiewicz *et al.* 2021; Qin *et al.* 2022).

Material Strength, Structural Constraints, and Deformation Challenges

During the experiments, it was observed that piezoelectric disks exhibited a high risk of fracture under excessive pressure. The observed behavior can primarily be attributed to the low thickness of the piezoelectric sensor, the relatively weak mechanical integration between the metal and ceramic layers, the high local load concentration, and the low mechanical resonance stiffness. These factors collectively limit the mechanical durability and energy conversion performance of the sensor under repeated loading conditions. Following mechanical reinforcement, the sensors produced strong and stable outputs at the milliwatt level. Similarly, numerous studies have reported that piezoelectric disks with thin ceramic layers commonly exhibit cracking, fatigue, and surface degradation (Duc *et al.* 2022; Thai *et al.* 2021).

The System's Scalability Potential

The use of 14 sensors within a single sidewalk module demonstrates that the system is scalable through multiple rectification stages as well as parallel or series connection configurations. For example, in a deployment consisting of 100 modules, the cumulative energy yield can be significantly increased under ideal aggregation conditions and by neglecting power conversion losses. Although the overall system output remains within the low-power micro-generation range, it may be sufficient to support the continuous operation of low-power street lighting systems or distributed sensor networks. These results demonstrate the scalability and practical potential of modular piezoelectric energy harvesting systems for smart city infrastructure.

Future Enhancement Suggestions

Based on the limitations of this study and the experimental findings, several directions for future research are recommended to improve the performance and practical applicability of piezoelectric energy harvesting systems. Sensor optimization may be achieved through the use of multilayer PZT structures, thick-film piezoelectric materials, piezoelectric fiber composites, and hybrid PVDF–PZT sensors to increase energy density and conversion efficiency. From a mechanical perspective, the incorporation of load distribution plates, elastomer-based shock-absorbing layers, and resonance-enhanced structural designs could improve load transfer, mechanical durability, and energy harvesting performance.

In addition, the electronic subsystem can be enhanced by integrating Maximum Power Point Tracking (MPPT) algorithms, intelligent energy storage units, and adaptive load management modules to maximize energy utilization and ensure stable power delivery. Finally, future studies should focus on long-term field validation through 6–12 months of continuous monitoring under high pedestrian-density conditions, together with comprehensive evaluations of water resistance, humidity resistance, and the effects of temperature variations on system reliability and durability.

Table 3 Literature Comparison on Piezoelectric Energy Harvesting

Study	Piezoelectric Type Used	Test Configuration	Maximum Output (V)	Power (mW)	Key Findings
Li et al. Gammaitoni (2012)	PZT-5H ADB	Laboratory test – 0.96 mm displacement	49.8	1235	Voltage increased by 356% using ADB
Kim - Kim Moure *et al.* (2016)	Rotary generator	Vehicle suspension system	-	59.45	High power generation from vehicle vibrations
Santos et al.	PZT cantilever	Highway prototype	-	0.68	Low power output with 11 months of durability
Mahmoud et al. Ambrozkiewicz *et al.* (2021)	PZT diaphragm	Sidewalk / floor tile	33.7	249.6	Successful driving of two LEDs
Alshammari - Khalid Yang *et al.* (2019)	Hybrid (Piezo + Solar)	Al-Haram case study	-	3-12	Suitable for high pedestrian and traffic density areas

CONCLUSION

It should be noted that the reported values correspond to peak instantaneous measurements obtained under controlled experimental conditions. Variations in pedestrian weight, stepping frequency, environmental conditions, and long-term material fatigue may influence the effective energy yield in real-world deployments. Future studies should incorporate statistical repeatability analysis, uncertainty quantification, and long-term performance monitoring to further validate system robustness. The literature reviewed, experimental prototypes, and field implementations examined within the scope of this study indicate that piezoelectric-based energy harvesting technologies are technically feasible and show promising potential under both pedestrian and vehicular traffic conditions. The findings suggest that similar trends are reported across different research groups, and that piezoelectric systems may represent a viable option for energy generation as well as for addressing the sensor requirements of smart transportation infrastructures.

Table 4 Energy Harvesting Test Results

Loading Type	Maximum Voltage (V)	Current (µA)	Power (mW)	Measurement Method
Single step (pedestrian)	2.4	79	0.1896	Voltage measurement (Oscilloscope)
Series LED load (2 units)	4.8	52	0.2496	Voltage measurement (Oscilloscope)
Vehicle load (wheel pressure)	61.6	112	6.899	Voltage measurement (Multimeter, OC)
Finger compression test	61.6	103	6.348	Voltage measurement (Multimeter, OC)
Finger impact	59.2	95	5.624	Voltage measurement (Multimeter, OC)

The voltage values reported in Table 4 were directly measured between the output terminals of the piezoelectric module under both open-circuit (OC) and loaded conditions. The corresponding current values were calculated using Ohm's law based on the measured voltage across the known load resistance. Consequently, the reported power values represent instantaneous peak power rather than continuous output power. It should be emphasized that the actual usable energy depends on the duration of the applied load as well as the efficiency of the rectification and energy storage circuitry. This calculation approach is widely adopted in piezoelectric energy harvesting studies due to the inherently high internal impedance of piezoelectric devices.

Across various experimental studies reported in the literature particularly those focusing on energy harvesting from human footsteps and low-amplitude vibrations, piezoelectric elements have been shown to produce peak voltages in the range of 20–33 V. With appropriate rectification and power-conditioning circuits, these voltage levels can be regulated to obtain a stable 5 V DC output suitable for low-power electronics. In previously reported large-area flooring prototypes (e.g., panels measuring approximately 455 × 405 mm), individual modules have been demonstrated to power LED loads, while multi-panel systems operating under high pedestrian density have achieved energy yields on the order of tens of watt-hours over extended operating periods. Such results highlight the potential of large-scale deployments as micro-generation solutions in locations characterized by sustained pedestrian flow, including institutional entrances, campuses, public transportation hubs, and metro stations.

Similarly, piezoelectric systems operating under vehicular traffic have demonstrated a higher energy generation capacity due to increased loading levels. In prototype-scale field implementations, PZT cantilever-based systems have been shown to continuously harvest energy at approximately 50 mWh per month from high-speed vehicle traffic, a level sufficient to power LED road markers or low-power sensor systems along a 200 m roadway segment. Moreover, the high durability exhibited by systems incorporating 16 piezoelectric cantilevers indicates that such configurations can be integrated into long-lasting infrastructure components. Experimental measurements demonstrate that each pedestrian step generates approximately 30–40 µJ of recoverable energy under controlled laboratory conditions. The associated peak power reaches approximately 0.19 mW; however, this value corresponds to instantaneous output rather than sustained power delivery. When accumulated over multiple pedestrian events, the harvested energy becomes sufficient to operate low-power electronic devices such as LEDs, temperature–humidity sensors, and IoT modules.

Due to the inherently low-current–high-voltage characteristics of piezoelectric systems, hierarchical energy management architectures incorporating rectification, filtering, and DCDC conversion stages are required. Simulation results further confirm that the two-loop cascade control (TLCC) strategy maintains a regulated 5 V output under dynamic input voltage fluctuations. When large-scale energy harvesting potential is considered, the importance of hybrid systems becomes particularly evident. While standalone piezoelectric elements exhibit limited power generation capability, hybrid systems that integrate piezoelectric components with triboelectric generators (TENGs), electromagnetic sensors, and photovoltaic surfaces have been shown to significantly enhance energy output, especially in areas with high pedestrian traffic. Evaluations conducted for locations with extremely dense pedestrian flow, such as the Al-Haram Mosque, indicate that the combined use of piezoelectric, triboelectric, and photovoltaic modules can enable the development of stable, continuous, and modular energy generation infrastructures.

In addition, piezoelectric materials based on PVDF, $BaTiO_3$, and MXene have been shown to exhibit longer service life and higher durability compared to conventional PZT elements, owing to their enhanced flexibility and fatigue resistance. Furthermore, cellulosic, biomimetic, and additively manufactured (3D-printed) composite structures are considered to represent an important development pathway for next-generation smart flooring systems.

Nevertheless, piezoelectric energy harvesting systems continue to face several important challenges that limit their widespread implementation. First, the energy generated by individual piezoelectric units remains relatively low, making standalone systems insufficient for high-power applications and highlighting the need for hybrid energy harvesting approaches. Second, long-term performance is strongly influenced by environmental factors such as temperature fluctuations, humidity, material fatigue, and repeated mechanical loading, all of which may reduce system reliability and energy conversion efficiency. Finally, the integration of piezoelectric devices into existing pavement and flooring infrastructure presents additional challenges related to structural durability, maintenance requirements, and their potential impact on pavement service life. Addressing these issues will be essential for the large-scale deployment of piezoelectric energy harvesting systems in future smart city environments.

Despite these challenges, the body of literature consistently indicates that piezoelectric-based energy harvesting is highly viable for low-power applications, aligns well with smart city visions, and is expected to play an important role in sustainable infrastructure projects. Applications such as smart lighting systems, road marking LEDs, traffic signalization, wireless sensor networks, IoT-based data acquisition systems, and security cameras can all be supported by energy harvested from piezoelectric panels.

This study experimentally quantified a peak energy of approximately 38 μJ per pedestrian step and demonstrated stable 5 V voltage regulation under ±20 V input fluctuations using TLCC control. In conclusion, piezoelectric energy harvesting represents an economical, environmentally friendly, sustainable, and low-maintenance method of electricity generation. Owing to the scalability of systems deployed in high-traffic areas, their potential to reduce energy costs, and their alignment with carbon-neutral city objectives, piezoelectric energy harvesting is a strong candidate to become a core component of future smart transportation infrastructures. In future studies, the development of higher-efficiency piezoelectric materials, the integration of deep learning–based energy management systems, and the wider adoption of hybrid energy harvesting solutions are expected to further enhance the large-scale applicability of this technology.

In parallel with this study, research and development activities related to the proposed piezoelectric sidewalk concept are ongoing. Future work is expected to focus on exploring sensor configurations with higher energy density, investigating the integration of hybrid energy harvesting approaches (piezoelectric–triboelectric–photovoltaic), performing longterm field evaluations, and examining scalable modular system designs. These efforts are intended to improve energy generation efficiency while facilitating the reliable and sustainable integration of the system into smart city infrastructures. In this context, the present study aims to provide a preliminary foundation that may support the future development and application of piezoelectric-based flooring energy harvesting technologies.

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Availability of data and material

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Ethical standard

The authors have no relevant financial or non-financial interests to disclose.

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