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A review of piezoelectric energy harvesting tiles: Available designs and future perspective

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ABSTRACT

Piezoelectric energy harvesting has played a vital role in powering several engineering devices and systems, where conventional power supply is either not possible or not desirable. Another perspective for piezoelectric energy is its utilization as a non-conventional clean energy source, harnessing the ambient mechanical vibrations. With the increasing global population and developing infrastructure, the load from human footsteps can be a source of significant amount of freely available mechanical vibration energy. The piezoelectric tiles are aimed at harnessing this otherwise wasted energy with minimum interference to the regular activities. This article aims to provide a comprehensive review of the technologies and methodologies that have been implemented in the literature. A comprehensive discussion on the various designs and mechanisms utilized in piezoelectric energy harvesting tiles is provided . Electrical circuits, which are crucial for successfully extracting the electrical energy from piezoelectric harvesters in usable form, are also discussed in detail. The feasibility aspects, from economic and energy perspectives, are also presented critically. Lastly, the challenges in the successful implementation of the piezoelectric tiles and their possible solutions are presented.

1. Introduction

In the last two decades, the energy crisis has emerged as one of the biggest global challenges, having a significant contribution from the explosion in the development of electronic devices [1]. Though we have high-capacity electrical energy generation sources such as hydro/thermal power plants, renewable and sustainable energy sources are now important to explore. The last decade witnessed many interesting energy harvesting techniques such as triboelectric [2], electromagnetic [3,4], piezoelectric [5], thermoelectric [6,7], and solar energy [8,9]. All these suggested energy sources are unparalleled due to their unique features. Among these, piezoelectric materials are very well known for their wide range of sensing and actuation applications. It is because of their functional solid-state coupling between electrical and mechanical forces. There are hundreds of new piezoelectric materials explored to fulfill society's thrust. These materials typically belong to the ferroelectric family. Mostly these materials are insulator ceramics. Broadly these are categorized based on their structures, compositions, and phases. Some of these materials belong to the family of $BaTiO_3$, $K_{0.5}Na_{0.5}NbO_3$, $Bi_{0.5}Na_{0.5}TiO_3$, $Pb(Zr,Ti)O_3$, ZnO, and a few polymers, as documented in the literature in various reviews and books [10-13]. In the context of piezoelectric energy harvesting, it has been explored for various kinds of mechanical energy harvesting from acoustics [14,15], water flow energy [16], wind energy [17], human motion [18], railway tracks [19], and highways [20]. Typically, energy outputs (from piezoelectric) are alternating current and voltage where current is of the order of micro-amperes and voltage is in the range of few volts [21]. With appropriate power conditioning circuits, the electrical output can be modulated. Recently, piezoelectric energy harvesting has been reported for water cleaning applications using piezocatalytic phenomenon [22]. There is a scope of water splitting for hydrogen generation using piezoelectric energy harvesting [23]. All these findings indicate that there is an untapped potential of piezoelectric energy harvesting techniques and devices. Piezoelectric energy harvesting devices such as shoes, tiles, pavements, roads, small energy devices of wireless sensor networks, and pacemakers have been reported in the past to utilize this potential to some extent.

Recently, research focusing on the energy harvesting from human

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movements and motions using the piezoelectric tiles, floors, and pavements has gained momentum and various studies have been conducted [24-36]. In general, the piezoelectric-based tiles can be perceived as regular ceramic and granite tiles fitted with piezoelectric materials which facilitate harvesting the waste energy resulting from human movements. These tiles can be planted over a larger area, thus serving as macro-power sources. Although a plethora of review articles discussing the current and future directions of piezoelectric energy harvesting are existing [37-42], they fail to present the to-date design and implementation of piezoelectric tiles and associated challenges in greater detail. This motivated the authors to consolidate the state-of-the-art mechanical designs, outputs, potential applications, and challenges associated with the piezoelectric tiles and pavements. A total of 120 publications have been reviewed in furnishing this comprehensive review on piezoelectric energy harvesting tiles. Piezoelectric energy harvesting through tiles has gained much popularity after 2014, and the number of publications has seen an increasing trend since then, as can be seen in Fig. 1, with the maximum number of publications in the year 2019.

The present review paper has been organized as follows: Section 2 provides an overview of the basics of the piezoelectric effect primarily in terms of governing equations and primary modes of operation. Section 3 is devoted to the various design types of piezoelectric energy harvesting tiles and fabricated prototypes. Section 4 details the electrical circuits interfaced with the piezoelectric tiles for power storage and optimization. Several case studies on the installation of the piezoelectric energy harvesting tiles and their feasibility assessment are presented in Section 5. Section 6 propounds the future prospects, several challenges, and feasible solutions associated with the implementation of the technology. Finally, the concluding remarks are presented in Section 7.

2. Fundamentals of piezoelectricity

2.1. Piezoelectric effect

The direct piezoelectric effect, first demonstrated by the Curie brothers in 1880 on quartz (SiO_2) single crystals [43], is the ability of a material to convert a mechanical load into an electrical response, such as an electric field, electric displacement, or polarization. Following the initial discovery, the Curie brothers also demonstrated the indirect piezoelectricity, i.e., an applied electric field could also induce a mechanical response of certain crystals. Although initially believed to be only present in a few special crystals, piezoelectricity has been discovered in a large number of ceramic materials and compositions, in addition to other material classes, such as polymers [44], bone [45], wood [46], and viruses [47]. Notably, the piezoelectric effect is not limited to materials with a spontaneous polarization but can also be found in nonpolar materials that lack a center of symmetry, such as zincite (ZnO) with a non-centrosymmetric hexagonal wurtzite-type crystal structure [48,49]. Despite this, however, the largest piezoelectric properties have been observed in perovskite crystals, where single crystals can display piezoelectric coefficients over three orders of magnitude larger than quartz that was originally demonstrated by the Curie brothers [50]. Due to the significant variability and tunability of the transduction properties as well as the capability to integrate piezoelectric materials in various processing methods, e.g., polycrystalline, single crystal, and films, piezoelectricity has become a vital enabling technology for a number of sectors, such as transportation, medical, military, energy, and consumer goods.

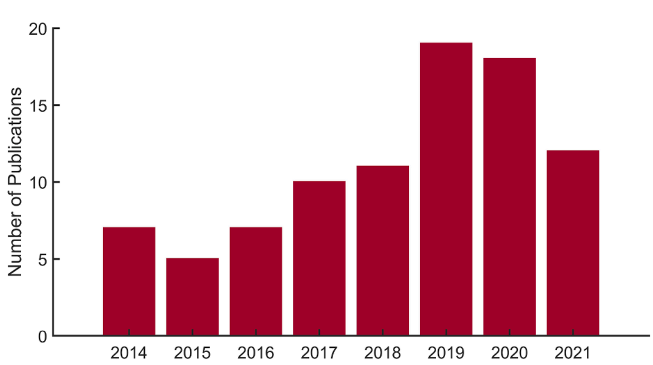

Fig. 1. The number of publications per year since 2014 on piezoelectric energy harvesting tiles. Data from 'scopus.com' using the keywords 'piezoelectric' and 'tile'. Only the publications related to energy harvesting tiles are selected.

Mathematically, the piezoelectric effect can be described as the electromechanically coupled linear relationship between mechanical (e.g., stress and strain) and electrical (e.g., electric field and electric displacement) field quantities. The strain charge form of piezoelectric constitutive law is given as,

$$\boldsymbol{S} = \boldsymbol{sT} + \boldsymbol{dE}, \tag{1}$$

$$\boldsymbol{D} = \boldsymbol{dT} + \epsilon^{T}\boldsymbol{E}. \tag{2}$$

Alternatively, in stress charge form,

$$\boldsymbol{T} = \boldsymbol{CS} - \boldsymbol{eE}, \tag{3}$$

$$\boldsymbol{D} = \boldsymbol{eS} + \epsilon^{S}\boldsymbol{E}, \tag{4}$$

where, $\boldsymbol{S}$, $\boldsymbol{T}$, $\boldsymbol{E}$, and $\boldsymbol{D}$ are mechanical strain, stress, electric field, and electric displacement, respectively. $\boldsymbol{s}$, $\boldsymbol{C}$, $\boldsymbol{d}$, and $\boldsymbol{e}$ are the mechanical compliance, stiffness, and piezoelectric coefficients' tensors in strain-charge and strain-charge forms, respectively. While ϵ^{T}, and ϵ^{S} are the dielectric permittivity matrices at constant stress and constant strain, respectively.

The crystal anisotropy is reflected in the non-zero coefficients, resulting in variations of the piezoelectric tensor for different crystallographic point groups [51]. For centrosymmetric crystals, namely materials with an inversion center, as well as point group 432, all piezoelectric coefficients vanish. For non-ferroelectric and non-ferroelastic crystals, such as zinc oxide (ZnO), aluminum nitride (AlN), and silicon oxide (SiO_2), the crystal symmetry plays an important role, as the appropriate crystallographic orientation is required to observe the piezoelectric effect and also results in the elimination of the piezoelectric effect for randomly oriented polycrystalline materials. In contrast, ferroelectric materials, which possess a spontaneous polarization that can be oriented by an external electric field, can display a piezoelectric response in crystallographically oriented configurations, such as single crystals, textured polycrystalline materials, and oriented films, as well as randomly oriented polycrystalline materials. This simplifies the manufacturing of sensors and actuators, both by reducing costs and improving integration into devices. Importantly, however, the mechanisms responsible for the reorientation of the spontaneous polarization can significantly affect the piezoelectric properties.

2.2. Extrinsic contribution to piezoelectricity

The piezoelectric response comprises both intrinsic and extrinsic contributions. The intrinsic contribution is understood to be due to field-induced lattice effects, *i.e.*, reversible polarization extension and rotation of the unit cell during application of an external field, which results in net changes to both the polarization as well as the unit cell strain. In contrast, extrinsic contributions are contributions that do not originate from the lattice, which typically is suggested to be largely due to domain wall and phase boundary nucleation and growth under applied external mechanical [52] and electric fields [53,54]. Other hysteretic processes, such as mobile defects, however, can similarly influence the piezoelectric response. For example, Schader *et al.* observed a significant increase in the frequency dispersion of the direct piezoelectric coefficient in co-doped hard $Pb(Zr,Ti)O_3$ with increasing temperature, which was suggested to be due to enhanced thermal mobility of defect associated [55]. Importantly, extrinsic contributions to the overall piezoelectric response can be significant, where it has been suggested that up to 20% of the piezoelectric response in single-crystal 0.67PMN-0.33PT originates from the formation of a multidomain state [56]. Other ferroelectric materials, such as $BaTiO_3$ and $Pb(Zr,Ti)O_3$ display irreversible extrinsic contributions on the order of approximately 40% [57] and 30% [52], respectively, above the lattice piezoelectric effect and reversible displacement of domain walls. The extrinsic contributions, however, increase with increasing applied maximum field amplitude, as higher external fields can induce additional hysteretic processes. In addition to applied fields, the mobility of domain wall and phase boundaries and, therefore the magnitude of the extrinsic contributions, depend significantly on a number of factors, such as crystal phase [52,58], crystallographic orientation of applied fields [59], dopants [60], temperature [59,60], applied bias stress [55], and microstructure [52]. These effects result in a piezoelectric response that is sensitive to both the amplitude of the applied external field as well as the application frequency [61].

2.3. Modes of operation

The piezoelectric effect results from the electromechanical coupling of strain/stress tensor and electric field vector. The nature and magnitude of the resulting piezoelectric effect are determined by the relative directions of the electric field and stress/strain with respect to the direction of polarization. Assuming the material to be poled in 3rd direction, different modes of operations can be identified as d_{ij}, where j is the applied strain/stress component, and i is the direction of the resulting electric field. The most common modes of operations for practical applications are d_{31} (transverse mode), d_{33} (longitudinal mode), and d_{15} (shear mode). These are schematically shown in Fig. 2 (A)-(C). The transverse mode is activated in the bending of beams and has been widely used in cantilever-based energy harvesting setups. The longitudinal mode requires the compression of the piezoelectric material in the direction of the electric field and, thus, generally appears in thick piezoelectric samples such as cylindrical ones. Shear mode of piezoelectricity is the least used mode for energy harvesting applications among the three.

In addition to individual operating modes, the utilization of a combination of different modes has also been utilized by researchers for achieving enhanced piezoelectric output. In this direction, the optimization of poling direction of piezoelectric materials has been devised as a way of activating multiple modes of operation simultaneously [62-64]. The relative rotation of the poling orientation with respect to the strain tensor components results in combined electrical output from longitudinal, transverse, and shear modes. The varying electric field direction in the material was also studied to harness the maximum potential of different modes by having d_{15} mode active at the mid of the beam where

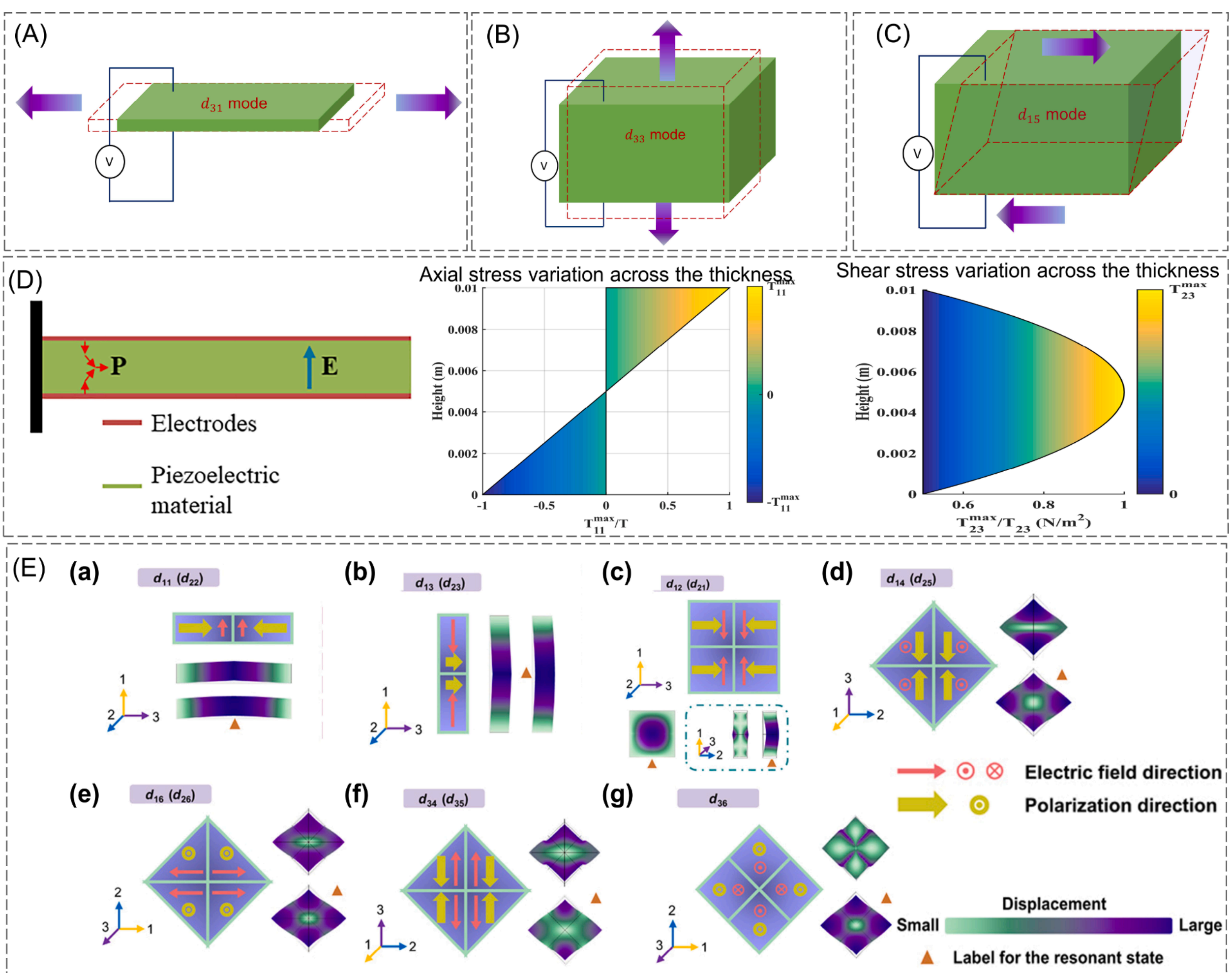

Fig. 2. Different modes of operation for piezoelectric energy harvesting; conventional modes, (A) transverse (d_{31}) mode, (B) longitudinal (d_{33}) mode, (C) shear (d_{15}) mode; (D) graded mode for having transverse mode at top and bottom of the beam, where axial stresses are maximum and shear mode at the center, where shear stress is maximum [64], (E) schematic of the metamaterial designed to realize all the shear normal and shear-strain modes, by programming the polarization and applied electric field in subunits [65], (a) d_{11} (d_{22}) mode, (b) d_{13} (d_{23}) mode, (c) d_{12} (d_{21}) mode, (d) d_{14} (d_{16}) mode, (e) d_{16} (d_{26}) mode, (f) d_{34} (d_{35}) mode, and (g) d_{36} mode.

shear stress is maximum and d_{31} mode at the top and bottom where axial stress is maximum. By employing the graded mode, as shown in Fig. 2 (D), a sensing voltage 15 times that in shear mode was observed, while actuation strain was observed to be 75 times that in shear mode. Yang et al. [65] designed metamaterials by introducing artificial anisotropy at the microscopic level to achieve all non-zero coefficients in the piezoelectric material matrix, in contrast to only five non-zero components in naturally occurring piezoelectric materials (Fig. 2(E)). This strategy was proposed to enhance the energy harvesting potential of piezoelectric ceramics several times due to all the possible modes acting simultaneously.

3. Designs of piezoelectric energy harvesting tiles

Due to increasing growth in population and enhanced energy demands for comfort and building services, the energy consumption of enclosed spaces has increased manifold in the past two decades [66]. However, a surge in the population and the time spent by the people indoors provides with scope to harness the mechanical energy due to human motion in the building sector. Piezoelectric energy harvesting tiles are a viable option for vibration energy harvesting from occupants' movements inside a closed space. An estimated energy generation of 1.1 MW h/ year has been shown in an education building, with a possibility of improvement up to 9.9 MW h/year [67]. Various designs have been employed by researchers to incorporate piezoelectric elements inside floor tiles for mechanical to electrical energy conversion. These designs, based on the type of piezoelectric element used, can broadly be classified into three main categories, namely, (i) cantilever type, (ii) curved type, and (iii) array/stacked type. These are discussed in detail in the following subsections.

3.1. Cantilever-based designs

Cantilever type piezoelectric energy harvesters are one of the most commonly used types for most applications, including energy harvesting tiles. Mechanical load from footsteps on the tile is transferred to the cantilever beam with embedded piezoelectric material. The bending of the cantilever beam results in axial stress on the piezoelectric material, which yields an electrical output. Both bimorph and unimorph beams can be used for this purpose. The superiority of the cantilever type piezoelectric harvester has been shown by comparing its output with a single-electrode mode triboelectric energy harvester with the same dimensions [68]. The power density of the piezoelectric harvester was found to be 5773.35 μW/cm^3 as compared to 752.34 μW/cm^3 of the triboelectric harvester.

In one of the initial studies on piezoelectric energy harvesting tiles, Hwang et al. [69] designed a three-layered piezoelectric energy harvesting tile with four cantilever type piezoelectric modules at the middle plate, as shown in Fig. 3. A 150 mm × 150 mm tile was used as the upper plate, on which the mechanical load from footsteps is applied directly. The bottom plate supports the tile through four springs of length 40 mm. The piezoelectric modules contain PZT-PZNM patches with dimensions 47 mm × 32 mm × 0.2 mm, placed on stainless steel plates of dimensions 67 mm × 37 mm × 0.2 mm as host structure. The vibration frequency of the piezoelectric module was made to match with the tile by altering the proof mass for enhancing the vibratory response. Circuit optimization was also performed through impedance matching, and at 15 kΩ of load resistance, the highest RMS output power of 770 μW with a peak of 55 mW. Theoretical analysis was carried out using a lumped parameter model, and the tile was manufactured based on the theoretical analysis. The tile was found to be capable of lighting a sixty-chip LED lamp through a single time-stepping by a 68 kg person. El-Etriby et al. [70] analyzed a fiber composite with PZT-5A particles embedded in an epoxy polymer matrix for applications in energy harvesting tile. The effective electro-elastic coefficients were calculated using a transformation field analysis (TFA), and finite element analysis

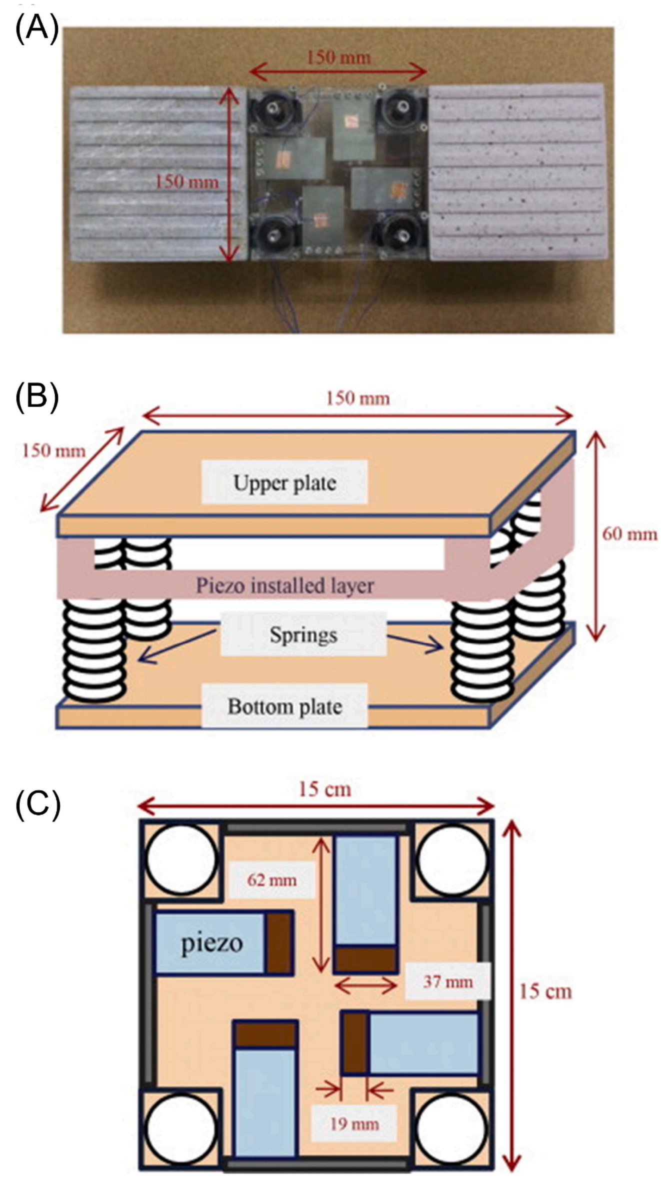

Fig. 3. The design of piezoelectric tile developed by Hwang et al. [69], (A) the prototype of piezoelectric energy harvesting tile, (B) schematic illustration of the tile, and (C) top view of the piezo installed layer.

was conducted to examine the dynamic behavior of the cantilever beam constructed using the campsite. Experimental studies were also conducted by applying a dynamic loading similar to that experienced by a subway train floor tile. Another cantilever type harvester was utilized by Kim et al. [71] in a piezoelectric energy harvesting tile for controlling electrical appliances. A novel piezoelectric material system 0.72Pb $(Zr_{0.47}Ti_{0.53})O_3$-0.28Pb$[(Zn_{0.45}Ni_{0.55})_{1/3}Nb_{2/3}]O_3$ + x mol% CuO (PZNxC) was designed for achieving the enhanced energy harvesting performance. A peak voltage of 42 V at 11 μA was obtained for a human weight of 80 kg.

The use of a permanent magnet at the location of the proof mass is also a concept widely utilized in literature for enhancing the output of piezoelectric energy conversion. Panthongsy et al. [72] employed a frequency up-converting mechanism in a piezoelectric energy harvesting tile to convert the low-frequency input vibrations to high-frequency vibrations of piezoelectric transducers. A set of 24 unimorph cantilever beams were mounted at a supporter, and a stainless-steel proof mass was placed at the free ends of the beams to increase the amplitude of vibrations, as shown in Fig. 4(a). Additionally, a permanent magnet is also

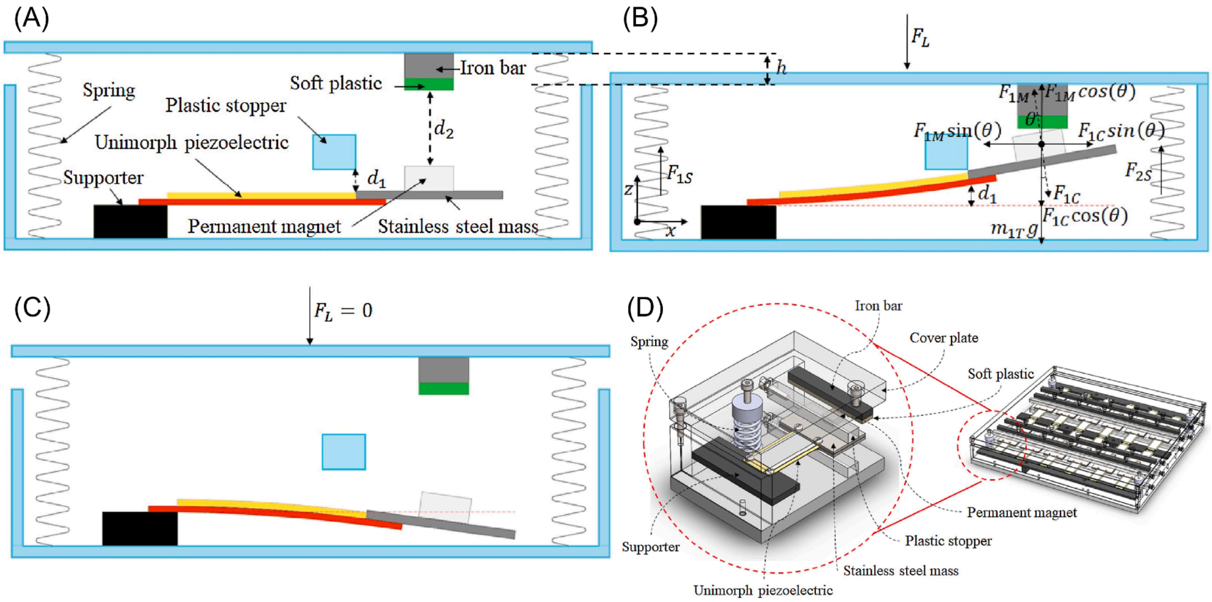

Fig. 4. Schematic demonstrating the working mechanism of the piezoelectric energy harvester with frequency up-conversion (A) waiting for load; (B) loaded, (C) unloaded states of energy harvesting floor tile, and (D) overall structure of the energy harvesting tile. [72].

mounted on the free end to attract the iron bar placed at the top layer. The top and bottom layers of the piezoelectric tile are separated by mechanical springs and the rest of the setup is placed in between. The working of the tile is sequentially demonstrated in Fig. 4(b). Initially, when there is no load on the tile, the air gap between the iron bar and permanent magnet prevents any attraction force. Upon application of force on the top of the plate, the air gap decreases, and the magnet is attached to the iron bar. In the unloading state, the restoring force of the springs becomes larger, and the magnet is separated rapidly from the iron bar. This sets the unimorph piezoelectric beams in vibrating motion. The energy conversion of the fabricated tile was analyzed by using both the finite element method (FEM) and experimental studies. The energy per step derived from the tile was 0.93 mJ, and it was able to power an accelerometer, a capacitive strain gauge, and a smoke detector for 1.60 s, 70.15 s, and 8503.03 s, respectively. A similar type of arrangement was employed by Isarakorn et al. [73,74] for designing a double stage energy harvesting floor tile. Jabbar et al. [75] designed a six cantilever piezoelectric energy harvesters-based tile with a permanent magnet and the free end of each cantilever, as shown in Fig. 5. The dimensions of the designed tile were 200 mm × 1500 mm × 500 mm, and the beams were vibrated at their resonance frequency through magnet interaction. Krishnasamy et al. introduced a two-phased triangular bimorph cantilever energy harvester for designing a piezoelectric energy harvesting tile for harvesting electrical energy twice per footstep [76]. FEM simulations of the tile were conducted using COMSOL Multiphysics software. While a pedestrian floor energy harvesting (PFEH) tile was designed by Jhun et al. [77], to accommodate variable widths of harvesters were designed for operating Internet of Things (IoT). Three different widths, 20, 30, and 40 mm of energy harvester, were used, and it was found that 40 mm piezoelectric energy harvester provided the maximum power output of 1.01 mW. A small LED display board with 30 LEDs was turned on using an undervoltage-lockout (UVLO) module.

3.2. Curved piezo element-based designs

Simple cantilever-based piezoelectric energy harvesters usually require a fixture for constraining one end of the beam, and a stopper is usually installed to prevent excessive deformation and damage to the piezoelectric material. Curved piezoelectric elements have been explored as energy harvesters inside smart tiles, which have a compact size and higher power output than the cantilever harvesters [78]. Due to the curved shape, these can easily be placed inside the tile in simply supported boundary conditions, without requiring additional fixtures at the ends. In this direction, an analytical and experimental investigation on a unimorph curved piezoelectric transducer (THUNDER transducer, developed by NASA Langley research center) for energy harvesting through a smart paver tile was conducted [79]. The piezoelectric harvester was placed on the center of a hexagonal tile, as shown in Fig. 6 (a). A prestressed contact was provided between the harvester and the top glass plate to ensure an immediate response to even a small loading applied on the tile. A maximum of approximately 85 μW power was generated by a 7 N force with a single curved piezoelectric transducer. A curved tile transducer was fabricated using ceramic grinding and polishing techniques for use in roadway tile applications [78,80]. Analysis of the tile transducer under different boundary conditions, excitation frequencies, and external loads was carried out before the packaging of

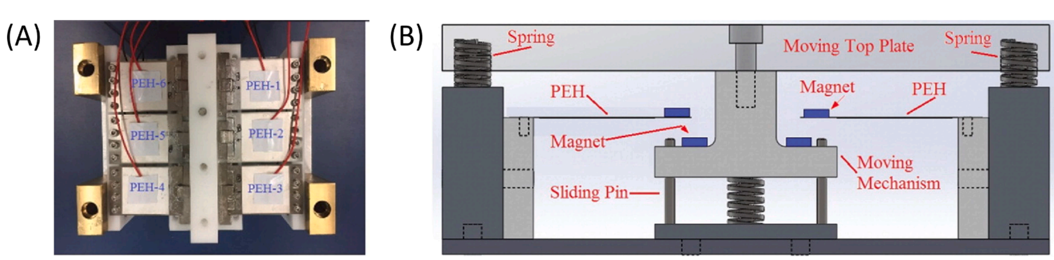

Fig. 5. The six cantilever piezoelectric energy harvester tile (A) top view of the size cantilever harvesters, and (B) schematic illustration of the tile with labelled parts[75].

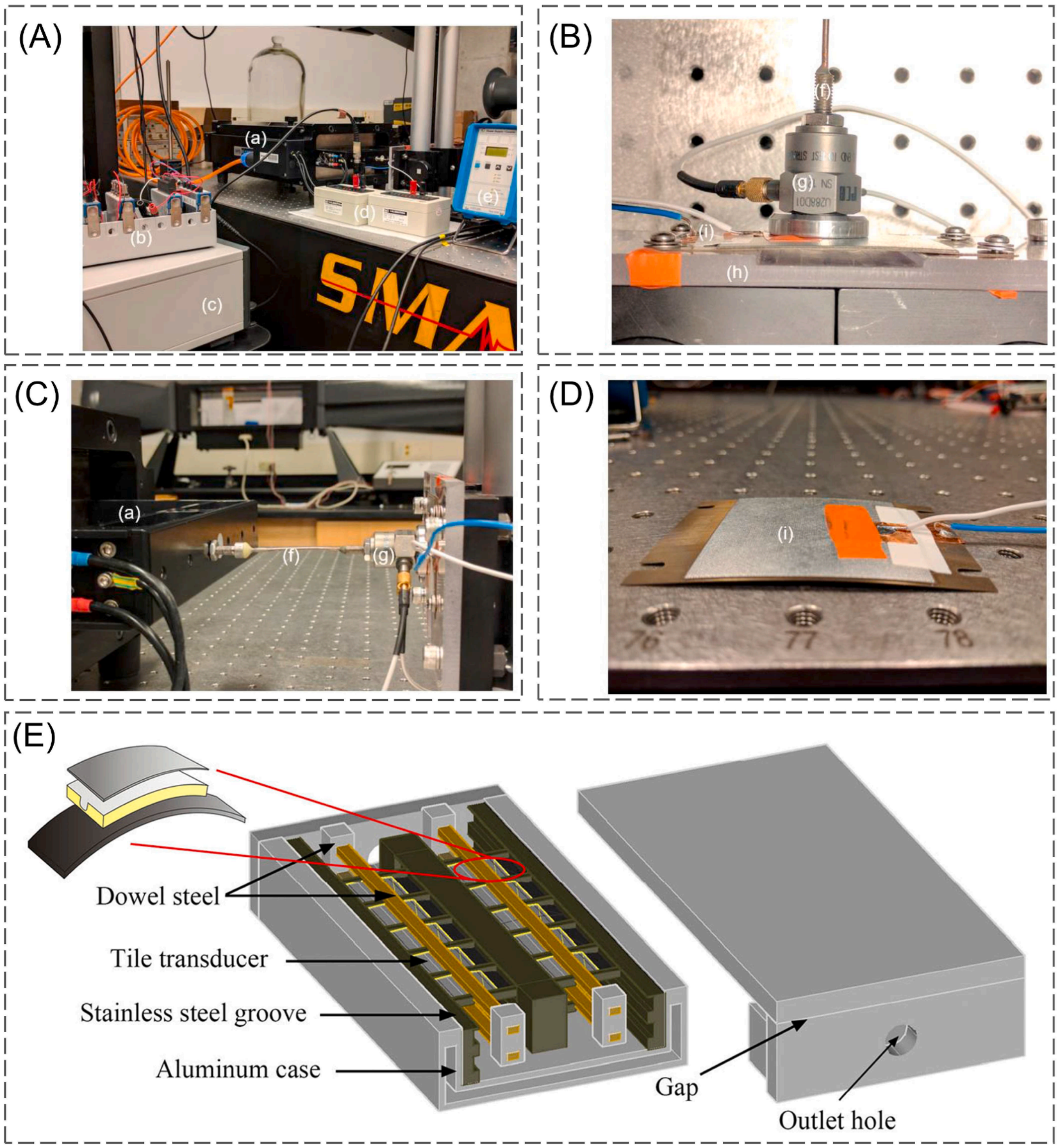

Fig. 6. (A-D) Schematic of curved piezoelectric smart paver tile [79], and (E) packaging design of a curved piezoelectric transducers' based tile [78].

tile, as shown in Fig. 6(b). Based on the studies, simply supported boundary conditions with concentrated load and a maximum allowable displacement of 0.614 mm were found to be the optimum parameters for the tile packaging.

3.3. Piezoelectric diaphragm-based designs

A piezoelectric diaphragm is made up of a thin piezoelectric disc placed on a metal sheet (usually copper) with a diameter larger than the piezoelectric disc. The diameter of the metal sheet is larger than the piezoelectric disc and a silver electrode is applied on the top of the disc, as shown in Fig. 7(a). When the diaphragm experiences a stretch or a shrink in its plane, a voltage difference is generated in the thickness direction. Piezoelectric diaphragms are the most easily available type of piezoelectric energy harvesters and can easily be installed at any plane surface using an adhesive. Due to this reason, a large number of research articles have focused on this type of element in piezoelectric tiles [81-89]. An 8 × 7 matrix of piezoelectric diaphragms of 50 mm outer diameter, connected through the conductive tape, was used as an energy harvester in piezoelectric tile, as shown in Fig. 7(A) [82]. A 1 mm gap was left below piezoelectric elements to allow the deflection, and a rigid plate was used to distribute the footstep force across the piezoelectric matrix. These tiles were installed on stairs to power emergency lighting and were able to generate up to 17.7 mJ of energy per activation, sufficient to turn on the light for 10.6 s. Moreover, preloading and area reduction was performed to optimize the performance of the piezoelectric harvesters. A similar type of piezoelectric energy harvester was used to harvest the electrical energy by transferring the human walking force to piezoelectric diaphragms using load transfer columns [86]. Additionally, a solar panel was also integrated with the tile to ensure uninterrupted energy generation even when there is no load on the tile. Several other studies have been conducted using a similar type of concept of using an array of piezoelectric diaphragms inside a floor tile [81,83,85,87-93].

Another way to enhance the net output of a piezoelectric energy harvesting tile is by employing stacks of PZT diaphragms under the top plate, as shown in Fig. 7(b) [84]. Nine stacks of piezoelectric diaphragms were used, each comprising of five piezoelectric diaphragms separated by a ring to allow the deformation. An analytical model was developed for calculating the optimal output voltage of the harvester subjected to a pulse excitation force. The experimental results were found to be in good agreement with the analytical results. The optimal output voltage was

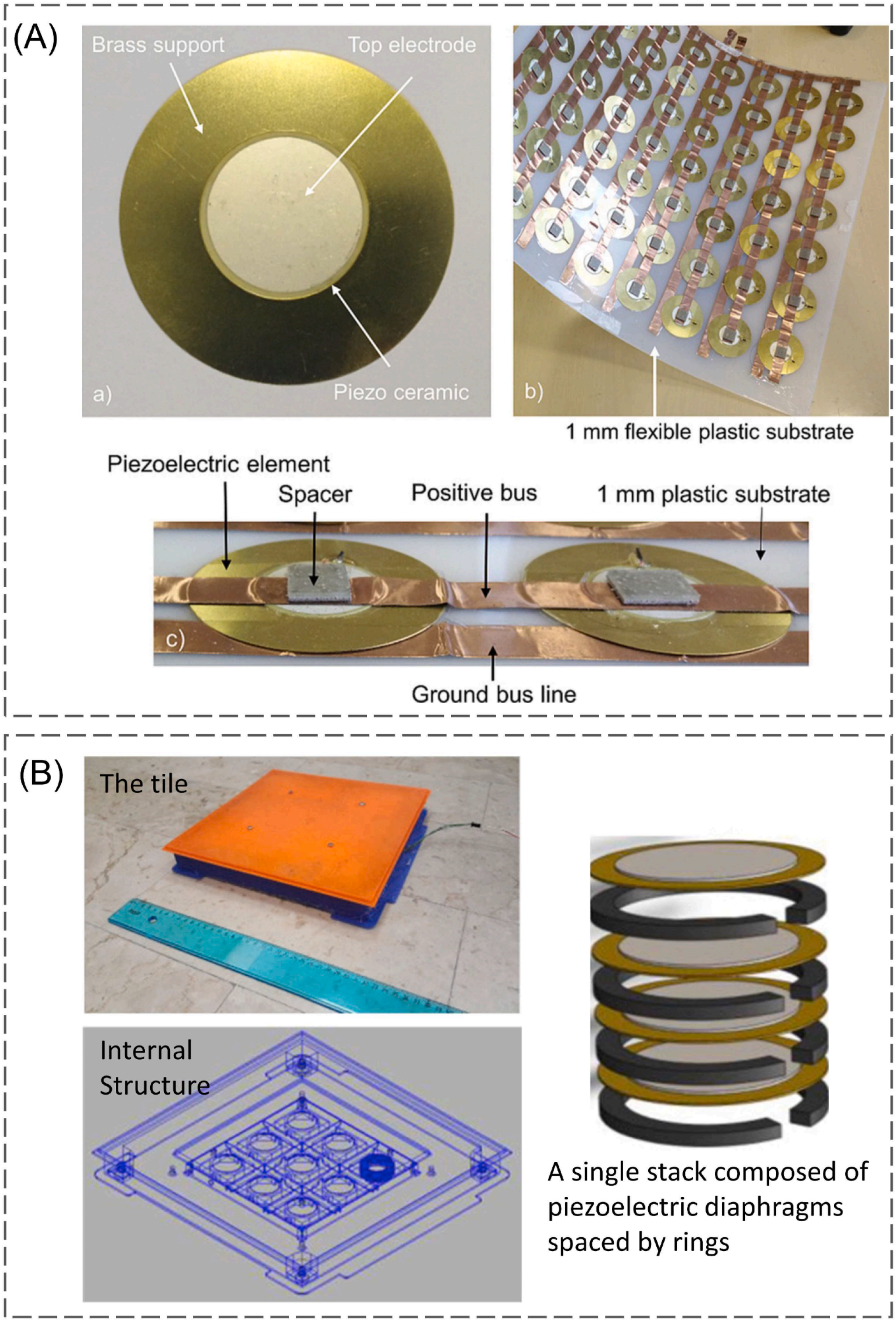

Fig. 7. Piezoelectric energy harvester tile based on (A) an array of piezoelectric diaphragms [82], and (B) a stacked piezoelectric diaphragms [84].

between 1/3 and 1/2 of the open-circuit voltage.

3.4. Miscellaneous designs

Apart from the most widely used three designs discussed above, there are other miscellaneous designs that can be a viable option for a piezoelectric energy harvesting tile. One of the sophisticated designs of the PEH for tile applications is a cymbal transducer. In this arrangement, a mechanism is designed such as the compressive load from the tile is converted to a tensile load on the piezoelectric element. Sharpes et al. [94] developed a floor tile with cymbal type PEH and termed it as STEP Tech (Smart Tile Energy Productions Technology), as shown in Fig. 8. A truss-like structure is designed to transfer the load of footstep such that the piezoelectric element is in tensile state of stress. An analytical solution was developed based on the truss analysis by the method of joints and was validated with the finite element analysis. For experimental analysis, a PZT element laminated with brass was designed as a cymbal transducer, and five of such transducers were installed inside an enclosure. The optimum number of transducers was decided based on various factors, such as the weights of an average person, maximum

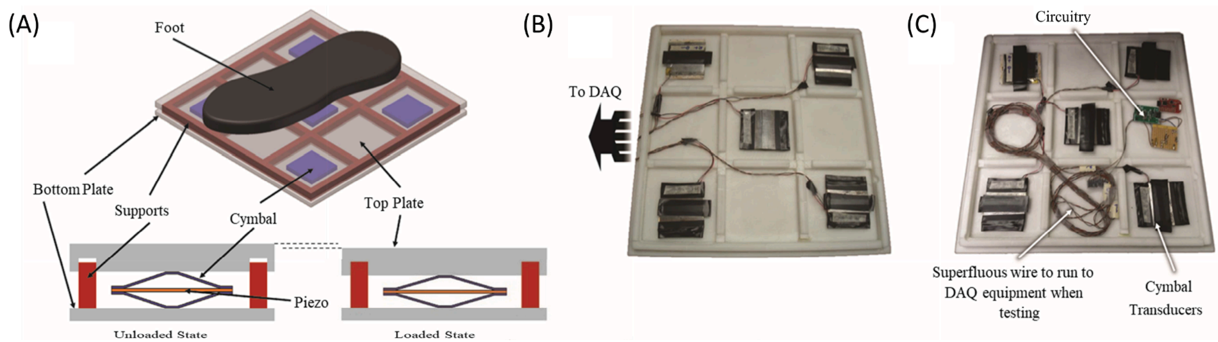

Fig. 8. Detailed illustration of the tile enclosure, (A) the cymbal energy harvester in loaded and unloaded states, (B) inside view of the fabricated enclosure for testing under human foot-steps, and (C) final tile enclosure with all the components internal to the tile [94].

energy harvested, and sensitivity of the tile. A peak voltage of 25 V was stored in a capacitor with 1 μF (energy can be inferred from the relationship $E = \frac{1}{2}$ capacitance × Voltage^2) for five cymbal transducers in parallel under 410 N simulated step. The tile was tested in a real-time application and was demonstrated to transmit a signal to remotely control a lamp. A compressive piezoelectric harvester was analytically investigated for piezoelectric tiles in stairways [95]. The characteristics of two types of commercially available tiles, Navy Type III and Navy Type V, were used to formulate the coupled electromechanical model. It was found that tiles with a highly nonlinear behavior substantially outperform the linear tiles. Also, the Navy type V tile was found to be better than the Navy Type III. Another compression-based piezoelectric energy harvesting tile was developed for utilizing the potential of human footsteps on a foot overbridge [96]. Fig. 9(a) shows the cylindrical compressive element used in the proposed design, and Fig. 9(b) shows the assembled arrangement of such multiple elements to form the energy harvesting tile. The tile was analyzed analytically using an equivalent system approach. The equivalent electrical and mechanical systems for a single piezoelectric element are shown in Fig. 9(c). An analysis of the force waveform experienced by the tile due to footstep was performed,

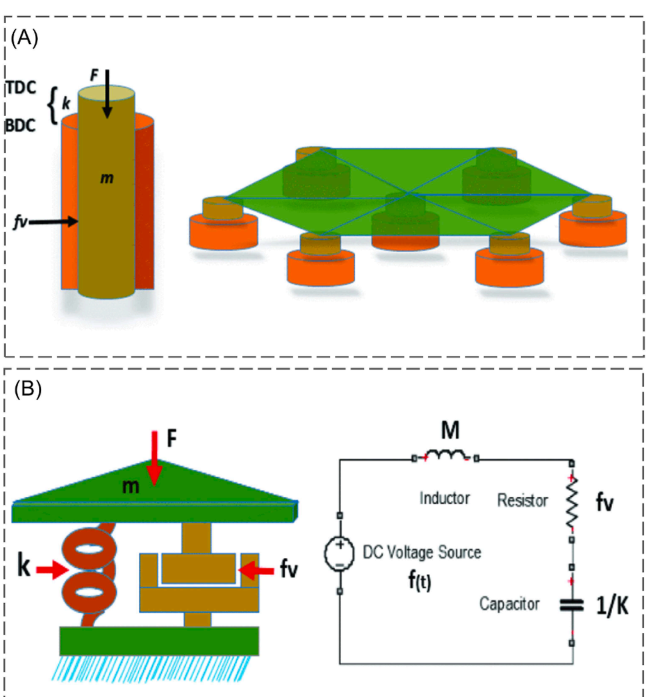

Fig. 9. (A) Schematic of a single piezoelectric transducer and assembled numerous piezo tiles, and (B) mechanical and electrical system design of the piezo tile [96].

and the cost and environmental aspects of these tiles were discussed. Another compressive element-based piezoelectric energy harvesting element, in the form of a disc, was used in a flooring tile to harvest energy and collect data for footsteps [97]. The floor tile was developed as a part of a smart city concept in Malaysia for reducing non-renewable energy consumption.

Force amplification mechanisms are often used in piezoelectric energy harvesters, where the piezoelectric element is surface bonded to a substrate and is subjected to tensile stress. In the conventional force amplification mechanisms, a large amount of force is absorbed by the substrate, which reduces the tensile stress in the piezoelectric element. This issue was overcome by employing a force amplification mechanism for achieving the bending of piezoelectric beams through a double-layer squeezing mechanism [98]. Two pre-curved aluminum beams, separated unevenly along the horizontal axis, were bonded with the piezoelectric clamped–clamped beams, as shown in Fig. 10. A rubber pillar was placed in between the two beams of every couple of beams, to enable the bending of the beams during foot strike. Although the peak-to-peak voltage increased with the increasing stroke of the upper plate, the stroke was limited to 5 mm. This was due to the reason that an excessively large stroke can give a sense of falling and is impractical for floor tiles. A voltage magnitude of 49 V (peak-to-peak) was achieved at a 5 mm stroke. The maximum power output of one beam was 134.2 μW for a step frequency of 1.84 Hz, while the total power output of 40 such beams under a single tile was 5.368 mW.

A dual-axial underfloor piezoelectric energy harvester was developed by Wu and Xu, using piezoelectric stacks [99]. The novelty of the energy tile was that it could utilize both the vertical and horizontal forces for energy conversion. The vertical force comes from the direct compression from the weight of the person stepping onto the tile, whereas the horizontal force is imparted to the tile by the lateral friction force between the tile and the human foot. The tile consisted of several conical transmission mechanisms (CTMs), two two-stage force amplifiers (TSFAs), and two piezoelectric stacks. The conical groove ends of the CTMs were connected to the upper plate and the position limiters to avoid any damage to the energy harvester. The conical ends of the CTMs were also connected to the input ends of the TFAs, and the piezoelectric stack was embedded into the TSFA, generating electrical power. The optimization for maximizing the power output of the tile was performed by first identifying the influencing parameter and then performing optimization using a genetic algorithm. The finite element simulations were performed using ANSYS Workbench. The average power output of the piezoelectric energy harvester was 1.25 mW and 0.85 mW under 5 Hz input force frequency with a magnitude of 100 N in vertical and horizontal directions, respectively. On the other hand, the harvested energy per footstep of a person weighing 62 kg was 7 mJ.

4. Electrical circuits: Types and optimization

The piezoelectric tiles are engineered to produce electrical energy by

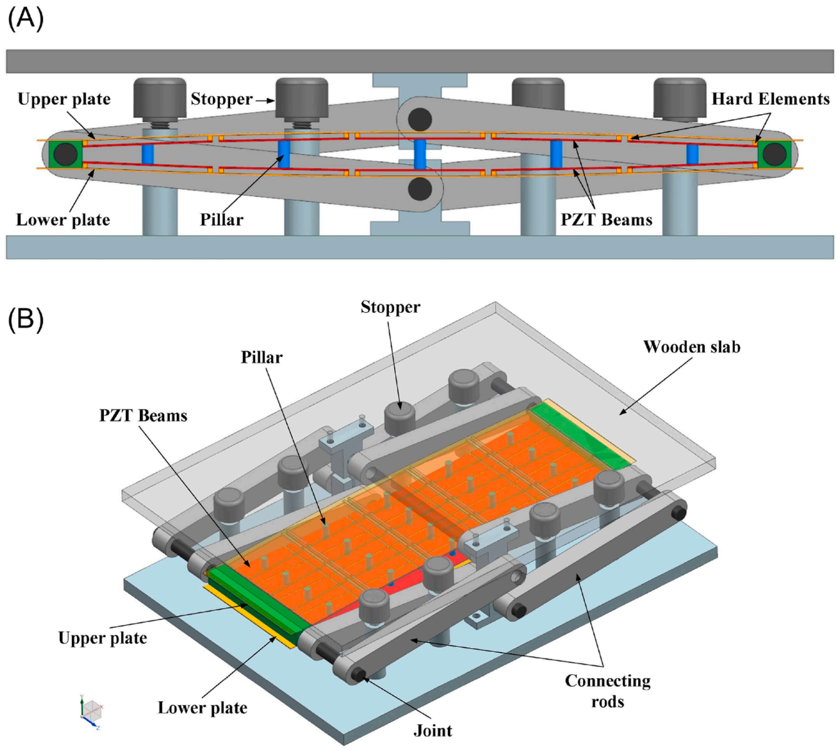

Fig. 10. Schematic of the energy harvesting tile using double layer mechanism for force amplification, (A) the front view, and (B) the isometric view.

converting the applied pressure to electrical signals using suitable transducers. These signals are converted into desired signals using rectifiers or power optimization circuits and stored in rechargeable batteries or used directly to run sensors or low-power electronic devices. Thus, electronic circuits have special significance for the utilization of power generated by piezoelectric tiles and can be categorized into different applications such as running sensors, and energy harvesting. The power obtained from a piezoelectric tile due to kinetic energy from human steps can be utilized into useful electricity for running various kinds of sensors installed for various applications. One such application of piezoelectric floor tile consisting of PZN0.5C supplied energy to a wireless sensor node (both transmitter and receiver) to run an electrical appliance by controlling the application switching in real-time [71]. A rectifier, capacitor, and voltage regulator optimized the power and provided sufficient voltage to transmit a signal via a wireless sensor (Fig. 11 (A)). The transmitted signal is received via a receiver, and a relay is operated to switch on the lamp, as shown in Fig. 11 (B).

The simplest form of a circuit to convert AC signals obtained from a piezoelectric tile energy harvester into DC signals consists of a bridge rectifier and a load tested as shown in Fig. 12(A) [77,90]. The harvester with variable harvested widths and loads was further used to provide enough power to run 30 LEDs using an undervoltage-lockout (UVLO) module with a turn-on voltage of 6 V under 1 kΩ load impedance [77]. If the voltage drops below the detection voltage of UVLO (4 V here), the internal circuit reaches a standby state. It is claimed that the power provided by the harvester is sufficient to run IoT sensors.

The use of a simple bridge rectifier in most circuits is enhanced by using multiple rectifiers in parallel, to sum up, the current and in series

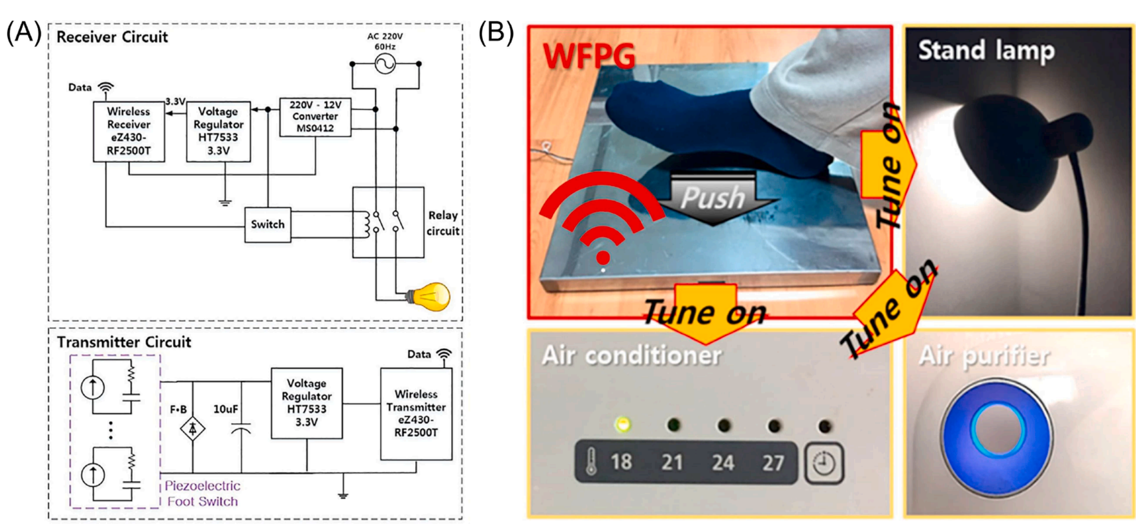

Fig. 11. (A) Circuit diagram of a wireless switch system operated by the floor tile. (B) Photograph of a wireless switch system synchronized with an air conditioner, a table lamp, and an air purifier, showing the capability for use in a real-time system [71].

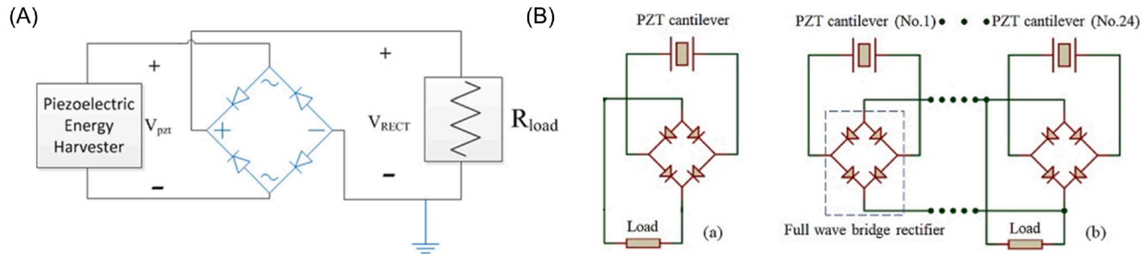

Fig. 12. (A) Circuit of an individual PZT cantilever [77]; (B) Circuit of electrically connected PZT cantilevers, rectifiers, and load resistors [72].

to sum up the voltage. In a study, a permanent magnet is used in place of a proof mass for enhancing the output of piezoelectric energy conversion, and a frequency up-converting mechanism is employed to convert the low-frequency input vibrations to high-frequency vibrations of piezoelectric transducers in piezoelectric tiles [72]. Due to the low output current obtained from PZT cantilever, the rectifier outputs of each are connected in parallel, and an optimal load resistor was used for evaluation, as shown in Fig. 12(B). A similar parallel combination of rectifiers is used in piezoelectric tile consisting of multiple PZT elements [84].

In another design [75], a six-cantilever piezoelectric energy harvesters-based tile using a permanent magnet is used to design a sustainable power supply for driving low power electronics. The circuit includes a DC-DC converter for impedance matching, transformer, switch, gate drive, and start-up circuits for self-powering and self-start of the circuit.

5. Available products and feasibility aspects

Apart from the significant amount of academic research, piezoelectric energy harvesting-based floor tiles are also being commercialized as a power source for low-power devices and sensors for interior spaces.

The feasibility of the piezoelectric-based energy harvesting tiles in terms of cost and power generation has been assessed in various operation environments in the past. These studies are usually conducted in public places with high pedestrian mobility. One such study was conducted for the central hub building (a library) at the Macquarie University in Sydney, where the floor area with the highest pedestrian mobility was first identified, and then the piezoelectric tiles deployment was proposed in the 3.1% most active floor area of the building [67]. For this purpose, a detailed description of the five-story library, in terms of traffic, mobility, the number of occupants, and working days in a year, was laid out. The building had a total floor area of 16,000 m^2, with a capacity of 3,000 seats for students and 150 working staff, and 353 working days throughout the year. The next step was to identify the locations of high traffic areas to maximize energy harvesting efficiency. This step becomes essential due to the high cost ($3850/tile) of the tiles selected for the study (commercially available Pavegen tiles). Based on the functional groups of students and staff, three hotspot areas were selected for the deployment of tiles, as shown in Fig. 13. The three hotspots, i.e., (a) the main entrance of the building, (b) the cafeteria, and (c) the books collection area, were estimated to have a cumulative daily crossing of 26,188 people. Finally, the power generation potential of the installation was calculated as a function of the number of people, electricity generated per step, number of tiles, and the enhancement rate due to the plucked method used to improve the energy harvesting efficiency. The economic and environmental benefits obtained by installing 1820 tiles, covering an area of 491.5 m^2 (3.1% of the total area) in the library building, were assessed, as shown in Table 1. The total amount of energy harvested was estimated to be 1.1 MWh/year, which could be increased to 9.9 MWh/year by integrating the plucked method.

The feasibility of piezoelectric energy harvesting floor adoption at Kuala Lumpur International Airport (KLIA) was carried out by Chew et al. [100]. The piezoelectric energy harvesting solution was proposed to complement already existing renewable energy systems, i.e., solar energy. The study inspected the potential factors that play an essential role in adopting the piezoelectric tiles at KLIA. A qualitative study was conducted based on a decision-making model for new technology adoption, known as TEMIF. Under this approach, the technical, environmental, managerial, intuitional, and financial factors are considered while evaluating the potential of fostering a new technology. Strategies to speed up the rate of adoption were also discussed briefly.

In another study, conducted by Elhalwagy et al., the feasibility of

Table 1
The estimated economic and environmental impact of the tiles' installation [67].

Enhanced annual generation (kWh/year)	Economic Benefits		Environmental Benefits	
	Energy Price (AU $/KWh)*	Running costs saving (AU$/year)	Emission factor ($kgCO_2$-e/KWh)**	Greenhouse gas mitigation ($kgCO_2$-e/year)
9888	0.055	543.84	1.07	10580.16

* Average annual electricity prices in New South Wales, Australia.
** Greenhouse gas emission factor for New South Wales, Australia from National Greenhouse Accounts (NGA) factors workbook.

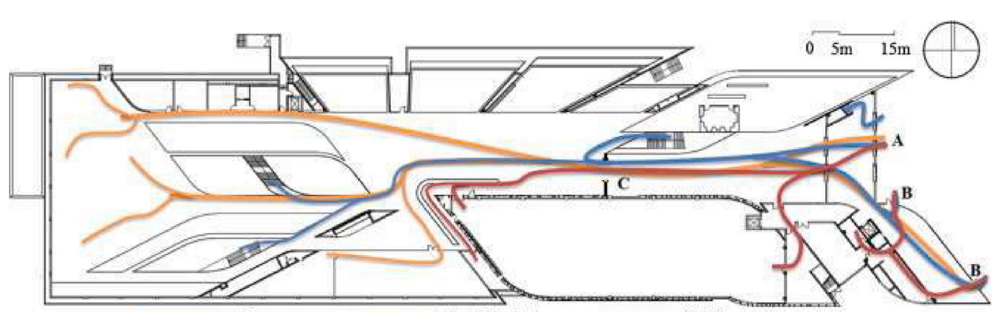

Fig. 13. Top view of library ground floor and the pathways followed by the students and staff [67].

piezoelectric tile installation was assessed by discussing the available piezoelectric technology and then conducting the case studies in two different operation environments [66]. For the assessment of feasibility, the power required and the number of steps per tile were used as the inputs, while the number of tiles needed and the cost feasibility were the outputs of the analysis. A private space (low pedestrian density) and a public space (high pedestrian density) were selected for the case studies for the sake of variety in area and density of the tile coverage. Ramses subway station was considered as the high pedestrian public space, which has a daily footfall of around 150 thousand persons and a power requirement of 10 MW. The low pedestrian private space was a residential apartment with five persons-family, with a power requirement of 10 kW. The feasibility of different available commercial tiles was carried out for both the spaces, in terms of cost and energy generation. Other case studies include the installation of piezoelectric tiles in a dance club in Rotterdam, Netherlands, as the world's first sustainable dance club; installation at the Tokyo train station's north exit; and the tiles installed at Ponte 25 De Abril bridge in Lisboa, Portugal [101]. The tiles were able to provide for the dance club's energy consumption by 30%, 65 % of the bridge's power consumption, and enough to power the station facilities such as automatic gates and electroluminescence display. Sports ground of Ahmadi township, developed by the Kuwait Oil Company, in Kuwait was considered as one of the sources of renewable energy using energy harvesting tiles [102]. This installation was a part of the redevelopment project designed for the sports ground to support Kuwait's 2030 energy vision of reducing the per capita energy consumption and increasing energy supply from renewables to 15% of the total consumption. The tiles were employed at jogging pathways and the game fields, which yielded a weekly energy output of 189 kWh and 20.9 kWh, respectively, with a total weekly energy generation of 209.9 kWh. The piezoelectric tiles were recommended as a part of the hybrid renewable energy generation system consisting of piezoelectric, solar, and wind energy harvesters. A similar type of study was conducted for a children's outdoor play area at El-Shams club in Cairo, Egypt, to evaluate the feasibility of piezoelectric energy harvesting through occupants' movement [103].

6. Challenges and future outlook

Piezoelectric-based energy harvesting tiles can be a viable renewable energy source, harnessing kinetic energy from human footsteps, with minimum interference with regular activities. The low power density as compared to other candidates in this category, such as solar and wind-flow-based energy harvesters, is sometimes cited as a shortcoming of the piezoelectric tiles. For outdoor areas, integration of piezoelectric tiles within solar modules has been implemented in the past to circumvent this issue. However, for indoor applications, piezoelectric tiles do not face any challenge from these energy harvesting techniques. The introduction of electromagnetic generator-based floor tiles in the open market has posed the biggest challenge to the commercialization of piezoelectric tiles. The leading technology in this domain is the Pavegen tiles, created by Laurence Kembell-Cook in 2009, with an aim to reduce the environmental issues related to energy generation [104], with the key mechanism being electromagnetic conversion. Since then, few other similar products have also been developed. Table 2 enlists such commercialized tiles developed based on piezoelectric and electromagnetic energy harvesters.

Other challenges facing the implementation of piezoelectric tiles are the brittle nature of most popular piezoelectric materials, relatively low power density compared to other alternatives, and the high cost of installation. The probable solutions to these challenges are,

Table 2
Energy harvesting floor tiles available commercially.

S. No.	Company	Geometry	Power	Life span	Energy generation technology
1	Pavegen [104]	Triangular with each side 500 mm	5 W continuous power for footsteps	20 years	Electromagnetic
2	Waynergy [105,106]	40 cm × 40 cm	10 W per step	20 years	Electromagnetic
3	Energy floors (The Dancer) [107]	70 cm × 70 cm × 20 cm	Up to 35 W sustained output from each module; 5–20 W per person	15 years	Electromagnetic
4	Energy floors (The Gamer) [108]		Up to 315 W peak power. This energy is sent back to the grid.	20 years	Combination of Solar and Piezoelectric
5	Energy floors (The Walker) [109]	60 cm × 60 cm	Up to 315 W peak power by 9 tiles. This energy is sent back to the grid.	20 years	Combination of Solar and Piezoelectric
6	Powerleap [110,111]	24 in. × 24 in.	about 1kWh per hour from 100 square meters with about 3,000–5,000 people each hour	20 years	Piezoelectric

1. Integration of solar, triboelectric, and electromagnetic modules with piezoelectric modules in energy harvesting tiles. Apart from providing energy output, piezoelectric module can be useful in data collection in commercial and industrial indoor spaces, such as the number of visitors, mobility and movement of visitors, duration of occupancy for a particular location, in order to optimize the usage of other appliances.
2. Instead of relying on only the transverse mode of operation, mechanisms can be devised so as to make the piezoelectric energy harvester work in multiple modes. The transmission of compressive load in the form of simultaneous compression, shear, and bending on the piezoelectric material would be ideal for this purpose.
3. The power density of piezoelectric materials can be enhanced to some extent by altering poling direction. This technique can simultaneously activate multiple modes of piezoelectricity, which are dormant otherwise. Two methods have been suggested for achieving inclined or tuned poling, i.e., modified electrode configurations [63] and cutting piezoelectric material at an angle from a normally aligned piezoelectric material [112].
4. Material based solutions such as piezoelectric – polymer composites [113], and auxetic structures [114,115] can be implemented for improved flexibility and power output.

7. Conclusions

Piezoelectric energy harvesting tiles are a plausible way to support clean and environment-friendly energy generation and reduce the reliance on fossil fuels for powering indoor appliances. This review dealt with various aspects of piezoelectric energy harvesting tiles, from material aspects to the feasibility of implementation. The different modes of piezoelectric energy harvesting are first discussed briefly, as it is crucial to understand the mechanism of mechanical to electrical energy conversion for the design of piezoelectric energy harvesting tiles. The design and mechanisms utilized in the literature for piezoelectric energy harvesting are discussed under four categories. The beam bending and piezoelectric diaphragm are the most commonly used designs in the tiles, mainly due to their ease of implementation and availability. Other designs, such as curved, cymbal type, stack type, and force amplification mechanisms, are also used for enhancing the effectiveness of piezoelectric energy harvesting in tiles. Since the electricity generated by the piezoelectric energy harvesters is directly related to the structural dynamics of the harvesters, it becomes essential to have optimal circuitry to harness this electricity in usable form. Further, charging batteries requires DC output, whereas piezoelectric energy output is AC, which calls for an AC to DC converter circuit. Also, the frequency and amplitude of the mechanical load coming from human footsteps vary in a broad range. A review on the electrical circuits for piezoelectric energy harvesting in general and for piezoelectric energy harvesting tiles, in particular, has also been presented for this reason. An overview of the feasibility aspects associated with the installation of piezoelectric energy harvesting tiles is also provided. The studies considering the cost and energy aspects of the implementation of these tiles have been discussed. Lastly, the challenges faced by the piezoelectric energy harvesting tiles in the form of competitor technologies and limitations of piezoelectric energy harvesting have been discussed. The possible solutions/suggestions to these challenges are also presented in the end.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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