DOI: https://doi.org/10.4038/jepsl.v14i1.7906

Journal of Environmental Professionals Sri Lanka: 2025 – Vol. 14 – No. 1

Piezoelectric Energy Harvesting from Human Energy Waste: A Review of Materials, Performance, and Environmental Potential

K.K.S. Owindi [1] and N. Arosha Hemali [2*]

[1] Department of Energy & Environmental Technology, Faculty of Technology, University of Sri Jayewardenepura, Nugegoda, Sri Lanka.

[2] Department of Energy & Environmental Technology, Faculty of Technology, University of Sri Jayewardenepura, Nugegoda, Sri Lanka

*Corresponding Author**
Email: aroshahemali@sjp.ac.lk

Abstract

Piezoelectric energy harvesting is a sustainable method of transforming mechanical energy from human motion into useful electrical energy. This review focuses on staircase-based piezoelectric tile systems that utilize human footsteps as an energy source. The study outlines the fundamentals of piezoelectricity, discusses material choices such as PVDF and PZT, and evaluates how factors such as tile thickness, applied force, load resistance, and step frequency influence output performance. Comparative analysis indicates that piezoelectric tiles can generate electricity at the milliwatt level, which can be used to power wireless sensors, lighting systems, and other low-power devices. Applications such as piezoelectric floors and smart shoes demonstrate how these principles can be scaled from wearable technologies to architectural installations. Overall, piezoelectric staircase systems represent a low-cost, eco-friendly solution for distributed power generation in high-traffic areas.

Key Words: piezoelectricity, waste, energy, electricity, smart

Introduction

Energy storage and renewable energy harvesting have been the subject of extensive investigation. The most common sources of power in modern life are solar, wind, geothermal, and tidal energy harvesters (Disssanayake et al., 2024) Renewable energy sources such as the Sun, tides, and wind are limitless and naturally renewed, in contrast to non-renewable energy sources like oil and natural gas. There are numerous uses for renewable energy, including the production of electricity, resources (such hydrogen and methane), and water treatment (like heating, cooling, transportation, purification, and desalination) (Chen et al., 2025). As global concerns about the depletion of natural resources, such as fossil fuels, and the ensuing degradation of the environment, such as greenhouse gases, have grown, attention is turning to renewable or alternative energy sources, such as hydropower, solar thermal power, photovoltaic power, wind power, tidal power, and bioenergy, to offer sustainable and alternative energy sources (Choo et al., 2025).

In the twenty-first century, achieving sustainable development has become a crucial worldwide concern. The fundamental shift from conventional fossil fuel-based energy systems to renewable sources including wind, solar, hydro, and biomass is at the core of this dilemma. This change is essential for maintaining long-term energy security, promoting social fairness through a just transition, and promoting inclusive economic growth globally, in addition to lowering greenhouse gas emissions and halting climate change (Supershi et al., 2024).

Systems known as piezoelectric energy harvesters use mechanical force as input and can transform it into an alternating current (AC) output. When paired with a full bridge rectifier, which is a power rectification component, the AC can be transformed into direct current (DC). This electrical energy can then be stored in capacitors or batteries or used directly in electronics (Crawleys and Luo, 2024) Both the overall population and the total number of automobiles on the planet are growing daily. The overall power consumption rate is likewise increasing. In order to reduce roadside electricity waste and enable controlled street light operation, a Piezo electricity generator is used in an intelligent lighting system. The light intensity in this system can be adjusted based on how cars or pedestrians appear on the road. In order to alert drivers when someone crosses a road at night, this system also adds a zebra crossing light (Kabir et al., 2019).

For instance, when shoes are designed with piezoelectric technology, the electrical energy generated by the pressure is detected by sensors within the shoes, transformed into an electrical charge by piezo transducers, and subsequently stored in batteries for use as a power source at a later time. Additionally, there are other uses for this power source, including supplying energy to sensors in remote locations, home appliances, and street lighting (Pendem et al., 2023; Ahmed et al., 2024) One project is the best conservative, sensible vitality answer for everyday civilization since it has been effectively attempted and completed. In rare circumstances, this can be utilized in rural places where control accessibility is either nonexistent or very limited. India is a developing nation where it is very difficult to manage the energy needs of its massive population. Depending on the power we give the piezoelectric sensor, we can use this task to regulate both AC and DC loads. Because it lowers control demand without harming the environment, this method offers efficient power generation in nations with big populations. In reality, just 11% of renewable energy sources support our vitality. In addition to resolving the energy crisis, this project has the potential to significantly alter the world ecology (Sukanya et al., 2024).

A piezoelectric energy harvesting system may be able to employ piezoelectric materials as a power source due to their unique properties. Anisotropic dielectrics are the general term for piezoelectric materials, some of which exhibit ferroelectric or non-ferroelectric characteristics (Miandoab et al., 2021). The conversion of mechanical energy to electrical energy in materials is made possible by the piezoelectric effect, a property unique to materials that results from the buildup of charges in response to compression or tension stress (Go et al., 2023).

Conventional steps are still utilized for floor steps. We believe that the energy may be used simply by installing a "Staircase Power Generation system." A lot of energy can be captured by installing this system in a rural building or in locations like train stations. The lights in rural areas or crowded areas like train stations, colleges, etc. can be powered by this energy (Kadu et al., 2016). Piezoelectric technology is one method for transforming the dynamic pressure from the staircase into a potential difference.

The applied pressure, which is determined using the formula;

Pressure = force/area, affects the amount of the potential difference (Yogeswaran et al, 2018)

Background

Named after the Greek term piezein, the Curie brothers originally described the piezoelectric phenomenon in 1880 (Liu et al., 2025).

When some materials experience mechanical stress or deformation, they can produce electrical charges, a phenomenon known as the piezoelectric effect.(Oladapo et al., 2023). When mechanical vibrations in a piezoelectric material are converted into electrical energy, which may then be captured, the piezoelectric effect takes place. By applying an electric field that causes the material to experience mechanical stress, the inverse piezoelectric effect can be seen. In order to achieve a higher output voltage than current technologies, an energy-efficient system design has been created in this study (Hassan et al., 2023).

Various type of piezo electric effect has been identified. Effects of piezoelectrics. The Curies referred to direct effects as the "primary" effect. -Electric polarization brought on by mechanical strain, which changes sign when the strain is reversed. The "reciprocal" effect, also known as the "converse effect," is the mechanical stress caused by an electric field that changes sign when the field is reversed. Every single piezoelectric crystal must inevitably show both the direct and reverse effects. Only when a dilatation in one direction is followed by an electric polarization in the same direction is the phrase "longitudinal effect" frequently used. The phrase "transverse effect" is frequently used to describe a dilatation perpendicular to the related electric field (Garimella et al., 2015).

The below figure is represented the simple way of generation of piezo electricity.

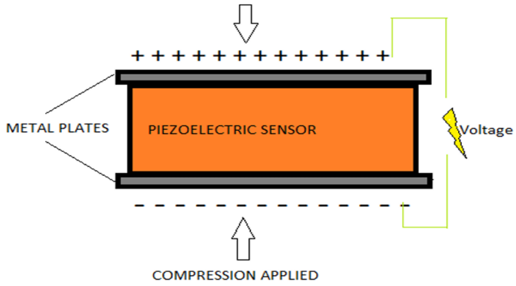

***Figure 01**: The piezo electric effect.Reproduced from Pendem et al, 2023*

Figure 2(a) illustrates the direct piezoelectric effect, which is defined as a change in electric polarization with a change in applied stress. The change in strain or stress in a material brought on by an applied electric field is known as the converse piezoelectric effect, and it is depicted in Fig. 2(b) (Garimella et al., 2015).

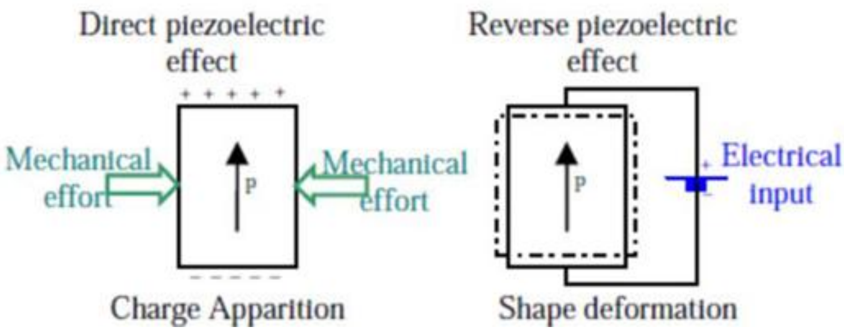

***Figure 02:** (a) The piezo electric mechanism.(b) The converse piezo mechanism. Reproduced from* Garimella et al., 2015*, License under CC BY-NC-ND 4.0.*

Since the energy harvester's mechanical design greatly influences the system's resonant frequency characteristics, a designer must be able to model, simulate, and optimize designs to fit new target applications in order to maximize power density. This can be accomplished by designing a system in which the energy harvester's resonant frequency coincides with the application environment's specific source frequency. In order to optimize power generation, the entire system will need to adjust and correct itself if damage causes the energy harvesting system or the source vibration characteristics change (Farnsworth et al., 2024).

A device that converts pressure or mechanical stress into electrical energy or the other way around is called a piezoelectric transducer. "Piezoelectric phenomenon" is the term used to describe the phenomenon of electrical charge generation in certain materials as a result of mechanical stress.

Figure 03*: The piezoelectric transducer,Reproduced from Ahmed et al., 2024) ,License under CC BY-NC-ND 4.0*

There are few types of piezoelectric transducers.Those are shown in Figure 4.

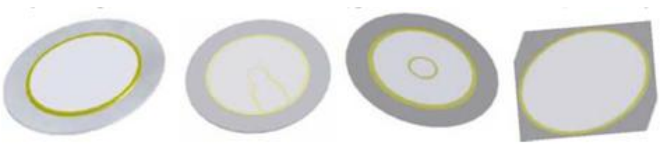

Figure 04*: (a) Two-terminal circle type,the metal is stainless stell,brass and nickal alloy;(b)Three-terminal circle with brim feedback,the metal is brass and stainless steel;(c) Three-terminal circle with centre feedback,the metal is brass and stainless steel;(d)Two-terminal square type,the type,the metal is nickel alloy.Reproduced from Garimella et al., 2015 License under BY-NC-ND 4.0.*

Methodology

In this review, the main factors influencing staircase piezoelectric energy harvesting were examined using a comparison method. While applied force and step frequency were evaluated based on typical human stair climbing, mechanical aspects like the number of piezoelectric crystals, tile material, and thickness were taken into account in relation to staircase dimensions and input voltage. The function of electrical characteristics, such as rectifiers, converters/inverters, and load resistance, in controlling the energy produced was also investigated. Using this paradigm, the impact of each parameter was examined using theoretical justifications and knowledge from earlier research, emphasizing the trade-offs between durability, efficiency, and power output.

Comparative Analysis of Key Parameters

Material Type

If a material produces an electric potential under mechanical stress and responds mechanically to an electric field, it is said to be piezoelectric. (Oladapo et al., 2023).

Mechanisms for converting environmental vibrations into electrical energy that may be stored and utilized to power other devices can be found in piezoelectric materials (PZT). PZT power generation can offer a typical substitute for conventional power sources required to operate specific kinds of sensors/actuators, telemetry, and MEMS devices, especially with the current explosion of microscale devices (Garimella et al., 2017). One best example for making tile using PZT, For charging low power devices for impulse power applications, a 5 gram impact mass of lead material is used as the hitting mass on a Lead Zirconate Titanate (PZT) patch, producing an output power of 9.072W at a resonance frequency of 177.143 kHz (Allamraju and Sri Kanth, 2016). It has been demonstrated that the greatest power produced by the piezoelectric's vibration is 2 mW, which is sufficient to charge a 40mAh button cell battery in an hour (Garimella et al., 2015).

With the ability to convert up to 80% of mechanical energy into electrical energy, lead zirconate titanate (PZT) is an extremely efficient piezoelectric material that is almost 100 times more effective than quartz. In comparison to polyvinylidene fluoride (PVDF), it also shows a larger piezoelectric voltage constant and a stronger capacity for voltage conversion. However, PZT is more costly than PVDF, difficult to manufacture in small amounts, and exceedingly fragile despite its greater performance. (Elhalwagy et al., 2017). Researchers examined the effects of applying a DC electric field (poling) on the structure and characteristics of three different types of PZT ceramics (5A, 5H, and 4D). Tetragonal and monoclinic crystal forms are typically mixed together in these materials. The structures grow increasingly deformed after poling, and the Curie point—the temperature at which a material loses its piezoelectric effect—shifts downward. The crystal's transition from tetragonal to monoclinic is plainly caused by the electric field in 5A and 5H, while it is somewhat less obvious in 4D (Tang et al., 2025).

Because of its appealing qualities, including piezoelectricity, light weight, high flexibility, thermal stability, and chemical resistance, polyvinylidene fluoride (PVDF) is one of the most promising piezoelectric polymers (Riwa et al., 2025).

Nanofillers improve PVDF's strength, flexibility, and piezoelectric performance, making it more effective. PVDF films may be easily and affordably produced by electrospinning, but research is still being done to improve their characteristics and investigate novel MPB-based processes to create highly competitive dielectric and piezoelectric materials (Veved et al., 2022). In its pure state, PVDF has poor piezoelectricity; however, fillers, copolymerization, and processing techniques such as electrospinning and poling can enhance its performance. Higher output is provided by PVDF/PZT composites, however the usage of lead raises environmental issues and emphasizes the need for environmentally benign substitutes. Notwithstanding these difficulties, PVDF has promise for energy harvesting, sensing, and medicinal applications, and computational research is aiding in the optimization of its characteristics (Riwa et al., 2025).

Table 01*: Various computational methods that are used to study the piezoelectric materials, and their corresponding advantages and limitations.Reproduced from* Riwa et al., 2025 *.,License under CC BY-NC-ND 4.0.*

Computational method	**method Applications**	**Advantages**	**Limitations**
Density Functional Theory	Study of electronic properties and design of new piezoelectric materials	Accurate electronic properties	Limited to small systems
Molecular Dynamics	Investigating the effect of defects, Investigating the polarization switching in piezoelectrics	Ability to depict the dynamic behavior for large systems	Only for short time scale Requires force field accuracy
Finite Element Analysis	Designing of piezoelectric sensors/actuator/transducers	Analyzing complex geometries and handling of various boundary conditions	Lack of atomic level accuracy

Phase Method Field	Investigating the ferroelectric domain structures and domain switching in piezoelectrics	Appropriate for multi phase systems with ability to capture the complex microstructural changes	To check.

Tile thickness

The ability of piezoelectric beams or tiles to harvest energy is greatly influenced by their thickness. The output voltage of floating piezoelectric devices increased by 59.2% when the beam thickness was increased from 1 mm to 1.5 mm, but only by 5.81% when it was increased to 2 mm. This shows that the return decreases with thickness, indicating that the ideal thickness of 1.5 mm offers the best trade-off between voltage generation and mechanical stability (Khorramdarreh et al., 2024).

Load resistance

Both the electrical load attached to the piezoelectric tile and its mechanical design affect its performance. Higher voltage and power output result from the increased mechanical stress caused by tilting the piezoelectric disks. At the same time, the collected energy can be effectively stored and released by the careful selection of electrical load components, such as resistors or capacitors. This increases the lighting duration even after the external load is eliminated, demonstrating that optimizing electrical load and structural design are essential for optimizing the practical applications of piezoelectric tiles (Miandoab et al., 2021).

The voltage output and power transfer efficiency of piezoelectric energy harvesting devices are directly impacted by the load resistance selection. Based on earlier circuit and simulation research, values of 1 kΩ, 5 kΩ, and 10 kΩ are chosen to cover a realistic range. These investigations show that while maximum power is usually reached at an ideal mid-range resistance, usually around 2.6 times the internal or reference load, voltage rises with increasing resistance. Finding the ideal load point for balancing voltage gain and power extraction efficiency is made possible by evaluating across this range (Khorramdarreh et al., 2024).

Applied force

The "Smart Shoe Electricity via Piezoelectric Transducers" study demonstrates how human footsteps may be used to generate electricity, highlighting the promise of piezoelectric devices as an inexpensive and sustainable energy source. Similar to the shoe-based approach, which used the repetitive force of walking to generate milliwatt-level electricity, staircase-integrated piezoelectric tiles can use foot pressure to produce voltages ranging from 7 V to 13 V depending on the applied weight (50–75 kg). Staircase installations offer a greater surface area and higher traffic volume, making them more feasible for powering low-power devices or for storage in supercapacitors and batteries, even though the smart shoe shows that it is possible to capture tiny quantities of energy from individual steps (Ahmed et al., 2024).

Table 2*: Applied weight vs voltage.Reproduced from* Ahmed et al., 2024*,Licensed under CC BY-NC-ND 4.0.*

Applied weight(kg)	Generated voltage(V)
50	7
60	9
70	11
75	13

Step frequency

Step frequency is also correlated with output power. Step frequencies of 0.95 Hz, 1.41 Hz, and 1.81 Hz were used in one experiments, respectively. With a step frequency of 0.95 Hz, the tested piezoelectric beam was able to produce a peak-to-peak voltage of approximately 52.2 V based on the output voltages. The peak-to-peak voltage was around 51.4 V when the step frequency was raised to 1.81 Hz. According to the test results, the peak-to-peak voltages were comparatively steady for a range of step frequencies. One possible explanation is because the slab board's stroke was limited. However, when the step frequency increased, so did the output power (He et al., 2019).

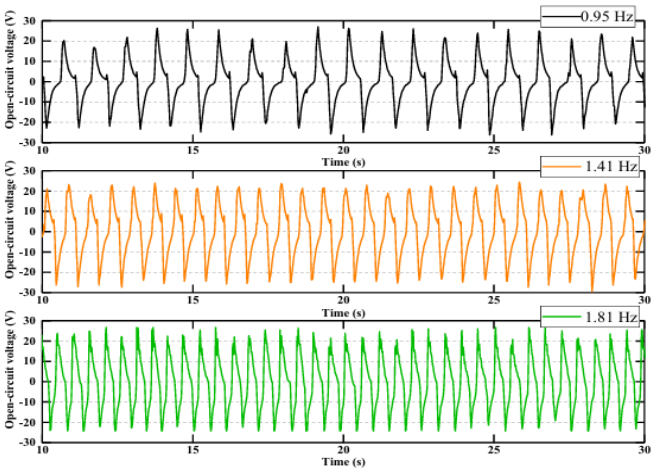

Figure 05: *The output voltages tested in di erent step frequencies. Reproduced from* He et al., 2019*, License under 4.0*

Conclusion

According to the review's findings, piezoelectric tiles embedded in staircases provide a practical and efficient method of capturing renewable energy from routine human activity. The efficiency and output of these systems can be significantly improved by optimizing key factors such as tile thickness, material type, applied force, and load resistance. Experimental data indicate that milliwatt-level power outputs and voltages ranging from 7 to 13 V are achievable. These outputs are sufficient to power small electronic devices or to store energy in batteries and supercapacitors. Piezoelectric systems can be integrated into public spaces such as train stations, universities, and urban buildings to support sustainable development and reduce reliance on non-renewable energy sources. To enhance the feasibility of large-scale applications, future research should focus on developing hybrid systems, reducing costs, and improving material durability.

References

Dissanayake, K., & Kularatna-Abeywardana, D. (2024). A review of supercapacitors: Materials, technology, challenges, and renewable energy applications. Journal of Energy Storage, 96, 112563.

Chen, X., Chen, A., Zhang, L., Yu, H., Mao, Z., Chen, Y., ... & Lu, J. (2025). Additive manufacturing of bionic interfaces: From conceptual understanding to renewable energy applications. *Advanced Bionics*, *1*(1), 57-82.

Choo, J. F., Ha, D. H., & Han, H. K. (2017). Evaluation of energy-producing capability from pedestrian-induced vibration in footbridge by a new Tuned Mass Piezo-Damper. *KSCE Journal of Civil Engineering*, *21*(6), 2322-2328.

Superchi, F., Moustakis, A., Pechlivanoglou, G., & Bianchini, A. (2025). On the importance of degradation modeling for the robust design of hybrid energy systems including renewables and storage. *Applied Energy*, *377*, 124645.

Crawley, F. J., & Luo, Z. (2023). High force compression mode to Shear mode piezoelectric energy harvesting. *Micro and Nano Engineering*, *23*, 100245.

Kabir, A. T., Nath, N. D., Hasan, F., Sadik, M. T., & Lisun, S. H. (2019, May). An intelligent street light system based on piezoelectricity generator with noticeable zebra crossing point and bus stand. In *2019 1st International Conference on Advances in Science, Engineering and Robotics Technology (ICASERT)* (pp. 1-5). IEEE.

Pendem, S., Suresh, K., Chilakala, S., Mubeen, S., & Shabana, N. (2023, May). Smart shoe based on piezo electric sensors for low power applications. In *INTERNATIONAL CONFERENCE ON ADVANCES IN SIGNAL PROCESSING COMMUNICATIONS AND COMPUTATIONAL INTELLIGENCE* (Vol. 2477, No. 1, p. 030005). AIP Publishing LLC.

Ahmed, S. T., Swamy, K. C. T., Reddy, O. S., Saqlain, M. M., Talha, S. M., Manohar, B., &

Kumar, Y. P. (2024). Smart Shoe Electricity Generation via Piezo-electric Transducers. In *E3S Web of Conferences* (Vol. 540, p. 13003). EDP Sciences.

Sukanya, K., Prashanth, A., Sravani, R., Vienala, S., Gangadhar, J., & Ugendhar, A. (2024). Arduino-Based Footstep Power Generation using Piezo-Electric Material. In E3S Web of Conferences (Vol. 564, p. 01002). EDP Sciences.

Miandoab, E. M., Jafari, A. H., & Valipour, A. (2021). Design of Piezoelectric Tile for Energy Harvesting: Experimental Approach. *Journal of Materials and Applications*, *10*(2), 83-89.

Go, J. C. T., Remolino, A. K. A., Sanchez, J. M. P., & Paz, K. E. (2023). Harvesting energy through piezoelectric tiles: a comparative study of wood, porcelain, and ceramic tiles. *EDUCATUM Journal of Science, Mathematics and Technology*, *10*(1), 1-6.

Kadu, S. M., Satpute, C. P., Bhoyar, S. M., & Motghare, S. U. (2016). Review paper on power generation by staircase. *international journal of science technology and engineering*, *2*(2), 852-854.

Yogeswaran, G., Vigneshwaran, S., Prithivirajan, K., & Premalatha, R. (2018). Harnessing The Energy Generated From Staircase Using Piezoelectric Technology.

Liu, L., Li, Z., Zhu, T., Sun, Y., & Xu, J. (2025). Advances in applications of low-dimensional piezoelectric materials in musculoskeletal system. *Materials Today Bio*, *33*, 102065.

Oladapo, B. I., Ismail, S. O., Kayode, J. F., & Ikumapayi, O. M. (2023). Piezoelectric effects on bone modeling for enhanced sustainability. *Materials Chemistry and Physics*, *305*, 127960.

Hassan, E., Kouritem, S. A., Amer, F. Z., & Mubarak, R. I. (2023). Acoustic energy harvesting using an array of piezoelectric cantilever plates for railways and highways environmental noise. *Ain Shams Engineering Journal*, *15*(3), 102461.

Garimella, R. C., Sastry, V. R., & Mohiuddin, M. S. (2015). Piezo-Gen-An approach to generate electricity from vibrations. *Procedia Earth and Planetary Science*, *11*, 445-456.

Farnsworth, M., Tiwari, A., & Dorey, R. (2014). Modelling, simulation and optimisation of a piezoelectric energy harvester. *Procedia CIRP*, *22*, 142-147.

Allamraju, K. V., & Srikanth, K. (2016). Design and experimental study of novel piezoelectric vibration energy impact mass harvester. *Procedia Engineering*, *144*, 560-567.

[Elhalwagy, A. M., Ghoneem, M. Y. M., & Elhadidi, M. (2017). Feasibility study for using piezoelectric energy harvesting floor in buildings' interior spaces. *Energy Procedia*, *115*, 114-126.

Tang, X., Hu, Z., Koval, V., Baxter, H., Eriksson, M., Whiteley, R., ... & Yan, H. (2025). Relationships between structure and properties in commercial lead zirconate titanate (PZT) piezoceramics. *Journal of Materiomics*, *11*(5), 101052.

Riwa, I. O., Banyikwa, A. T., Costa, R., Veved, A., Babu, N. S., & Sahini, M. G. (2025). Advances in copolymers based on polyvinylidene fluoride (PVDF) and their composites for piezoelectric energy harvesting. *Resources Chemicals and Materials*, 100124.

Veved, A., Ejuh, G. W., & Djongyang, N. (2022). Review of emerging materials for PVDF-based energy harvesting. *energy reports*, *8*, 12853-12870., doi: 10.1016/j.egyr.2022.09.076.

Khorramdarreh, E. R., Mohammadi, M. M., & Ghazanfarian, J. (2024). A novel floating piezoelectric energy harvesting from water waves: fully-coupled simulation. *arXiv preprint arXiv:2306.11901*., doi: 10.1007/s40430-024-05152-x.

He, M., Wang, S., Zhong, X., & Guan, M. (2019). Study of a piezoelectric energy harvesting floor structure with force amplification mechanism. *Energies*, *12*(18), 3516., doi: 10.3390/en12183516.