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Research Paper

Perlas (Piezoelectric energy for residential lighting and advance solutions): an arduino uno-based piezoelectric energy harvesting system for residential lighting applications

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ABSTRACT

This study explores the development and testing of a piezoelectric energy-harvesting prototype designed to convert mechanical stress from foot traffic into electrical power for residential lighting applications. With the increasing demand for sustainable energy solutions, piezoelectric sensors present a viable alternative for generating electricity from everyday activities. The prototype consists of piezoelectric sensors integrated into a flooring system, an Arduino Uno for energy tracking, a voltage regulator, and an energy storage component. A series of experiments were conducted to evaluate the system's efficiency, focusing on the relationship between applied force and voltage output. The results revealed a strong positive correlation ($r = 0.92$) between mechanical stress and energy generation, indicating that increased force leads to higher voltage output. Additionally, an ANOVA test confirmed a statistically significant difference ($p < 0.05$) in energy output across varying pressure levels, demonstrating the effectiveness of the system in energy harvesting. The prototype successfully stored harvested energy and powered LED lights, validating its potential for practical applications. However, improvements in energy storage capacity and circuit efficiency are necessary for large-scale implementation. This study highlights the feasibility of integrating piezoelectric energy harvesting into residential settings, contributing to the advancement of sustainable and renewable energy solutions. Future research should explore optimization techniques, larger-scale applications, and economic feasibility assessments to enhance its viability for broader use.

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1. INTRODUCTION

Background of the Study

The global demand for reliable energy solutions continues to rise as energy consumption increases in tandem with population growth and economic expansion. Modern societies rely heavily on electricity to power homes, industries, and essential services. However, the surge in energy demand places immense pressure on existing power grids and fossil fuel-based energy sources, contributing to environmental degradation and climate change. The depletion of non-renewable energy resources, rising electricity costs, and frequent power outages highlight the urgent need for sustainable and efficient energy alternatives [6].

One promising solution is piezoelectric energy harvesting, a technology that converts mechanical stress or deformation into electrical energy. Piezoelectric materials generate electric charge when subjected to mechanical force, making them suitable for capturing energy from human activities such as walking, jogging, or even routine movements in buildings [3]. These materials function in three primary modes: parallel shear (d15), longitudinal (d33), and transverse (d31), each with distinct applications depending on the type of mechanical stress applied [2] . By embedding piezoelectric sensors in commonly used surfaces, such as floors or staircases, kinetic energy from daily human activities can be harvested and transformed into useful electrical power.

Extensive research has been conducted globally on the potential of piezoelectric energy harvesting. Studies have explored its applications in wearable devices, roadways, and public infrastructure. According to Beddows and Mallon (2018), piezoelectric sensors can convert mechanical vibrations and pressure into alternating current (AC), which is then rectified into direct current (DC) and stored in a battery or capacitor. This stored energy can power small electronic devices or be integrated into larger energy systems. In their study, an Arduino Uno microcontroller was used to monitor the stored energy, regulate voltage, and manage device operation efficiently.

Hoo and Ibrahim (2019) expanded on this concept by testing piezoelectric energy harvesting systems using a breadboard setup before permanent installation. Their research emphasized the importance of user feedback in refining system performance, ensuring optimal energy conversion rates, and enhancing the overall efficiency of energy-harvesting modules. Other studies have examined the integration of piezoelectric technology into smart city designs, wherein sidewalks, roads, and public transportation systems serve as sources of sustainable energy through embedded piezoelectric materials [1].

In Southeast Asia, where rapid urbanization and economic growth drive energy consumption, researchers have investigated alternative energy sources to reduce dependency on fossil fuels. Studies in countries such as Japan and South Korea have demonstrated the feasibility of using piezoelectric flooring in train stations and pedestrian walkways to generate supplementary power for lighting systems [12]. However, in the Philippines, research on piezoelectric energy harvesting remains in its early stages, primarily focusing on conceptual frameworks rather than real-world applications. While renewable energy sources such as solar and wind power are widely studied, there is a lack of research on implementing piezoelectric systems for residential use.

Despite ongoing efforts to develop sustainable energy solutions, power shortages continue to affect Filipino households, particularly in rural areas where access to electricity is inconsistent. Current renewable energy initiatives in the country focus mainly on large-scale solar farms and hydroelectric plants, with limited attention given to small-scale, household-based energy harvesting technologies [5]. This gap underscores the need to explore alternative methods of energy generation that are both sustainable and feasible for everyday use.

While global studies highlight the effectiveness of piezoelectric energy harvesting, the integration of this technology into residential energy solutions remains underexplored. Most existing research focuses on industrial or commercial applications, with little emphasis on household-based implementations. Furthermore, the efficiency and practicality of piezoelectric sensors in small-scale residential settings require further investigation.

Given the Philippines' growing energy demand and frequent power interruptions, this study seeks to address the gap by investigating the feasibility of deploying Arduino Uno-based piezoelectric sensors for energy harvesting through pressure. By capturing mechanical energy from human movement and converting it into electrical power, this study aims to provide a sustainable and innovative solution to energy shortages. The system involves transforming mechanical energy into electrical energy, which is then stored and monitored using an Arduino Uno microcontroller. The microcontroller regulates voltage and manages stored energy, ensuring that it can be efficiently utilized for lighting and other essential household applications.

As environmental concerns continue to drive the search for alternative energy sources, technologies that harness mechanical energy from human activity offer a promising path toward sustainability. This study highlights the principles of piezoelectricity, system design considerations, and potential applications in residential environments. By demonstrating the viability of piezoelectric energy harvesting, this research contributes to the broader goal of promoting energy efficiency and reducing reliance on conventional power sources.

This study is motivated by the increasing need for sustainable energy solutions in the Philippines, where power shortages and high electricity costs pose significant challenges to households. By investigating the deployment of piezoelectric sensors for energy harvesting, this research aims to bridge the gap between theoretical frameworks and practical applications. The findings of this study will provide valuable insights into the potential of piezoelectric energy as an alternative power source, ultimately contributing to a greener and more energy-efficient future.

Objectives of the Study

This study aims to develop and test a prototype of a piezoelectric energy harvesting system utilizing Arduino Uno-based sensors for residential lighting applications. Specifically, it seeks to:

1. Design and construct a prototype piezoelectric energy harvesting system that captures mechanical energy from applied pressure and converts it into electrical energy.
2. Integrate and program an Arduino Uno microcontroller to monitor the stored energy, regulate voltage, and manage the output for lighting applications.
3. Evaluate the efficiency of the prototype in generating and storing electrical energy under controlled testing conditions.
4. Assess the functionality of the system in powering LED lights and ensuring a stable energy output for practical household use.

Research Questions

This study seeks to answer the following research questions:

1. How can a piezoelectric energy harvesting prototype be designed and developed for residential lighting applications?

2. How effectively does the Arduino Uno-based system monitor, regulate, and store the harvested energy?
3. What is the energy output and efficiency of the prototype under different pressure conditions?
4. How functional and reliable is the prototype in sustaining LED lighting over a specific period?

Null Hypotheses (H_0)

To evaluate the performance of the prototype, the study will test the following null hypotheses:

H_{01}: The piezoelectric energy harvesting prototype does not generate a significant amount of electrical energy from applied pressure.

H_{02}: The Arduino Uno-based system does not effectively monitor, regulate, and store the harvested energy.

H_{03}: There is no significant difference in the energy output of the prototype under varying pressure conditions.

H_{04}: The prototype is not functionally reliable in sustaining LED lighting for a practical duration.

Scope and Limitations

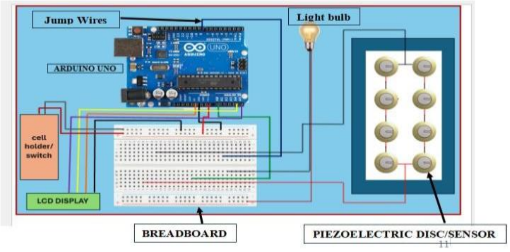
The study on “Piezoelectric Energy for Residential Lighting and Advanced Solutions” is aimed at investigating utilization of piezoelectric materials for harvesting energy from the vibrations in homes for power residential lighting and other intricate solutions. Mainly, it concerns the ways in which this energy can be used to fuel residential lighting and other smart solutions including small electronic devices and sensors. The domain focuses on reviewing the conversion efficiency from piezoelectric materials in terms of the energy output and the endurance of the material and the usability of these systems into the home infrastructure.

Conceptual Framework

Table 1. The Conceptual Framework

INPUT	PROCESS	OUTPUT
- Piezoelectric sensors - Arduino Uno microcontroller - Energy storage components (battery/capacitor) - Voltage regulator - Residential flooring integration	1. Design and development of the prototype 2. Integration of piezoelectric sensors into a flooring system 3. Configuration of Arduino Uno for energy tracking and regulation 4. Testing and performance evaluation of the prototype 5. Refinement based on collected data	- A working prototype of a piezoelectric-based lighting system - Data on energy output and efficiency - Feasibility analysis for residential use

Figure 1. The Schematic Diagram on PCB Board



As seen in Figure 1, a circuit diagram of a project that involves an Arduino Uno, a breadboard, a cell holder/switch, an LCD, Piezo discs/sensors and a bulb. It is a cell holder/switch which connects and supplies power to the circuit and to the breadboard and the Arduino. The lcd display is used for the display of the information and the Arduino is accordingly interfaced to the LCD Display. In this case, the Piezoelectric discs/sensors are interfaced with the breadboard and a microcontroller in the form of an Arduino to get an input. If pressure is applied to a Piezoelectric disc, then it produces a voltage with the help of which Arduino can read. This input is received by the Arduino which in turn controls the light bulb either switching it off/on/ and controlling the brightness. The specific functionality of a circuit depends on the code which is uploaded to that Arduino.

2. RELATED WORKS

The increasing demand for clean and sustainable energy has prompted global research on energy harvesting technologies. According to [2], reliable energy solutions are essential due to rising global energy demands and environmental concerns. The growing population and industrialization have led to an urgent need for alternative energy sources. Piezoelectric tiles in public spaces, such as train stations and roads, have been explored as a solution to reduce dependence on centralized power grids and minimize CO_2 emissions.

Similarly, [4] emphasized the renewed interest in piezoelectric materials as an efficient method for harvesting energy from human-surrounding environments. These materials convert ambient mechanical energy, such as vibrations and foot traffic, into electrical energy that can be stored and used for powering devices. Applications have been tested in airports and railways to lower energy costs and promote sustainable power generation.

The significance of human movement as an energy source was highlighted by Moussa (2021), who proposed utilizing piezoelectric tiles in densely populated areas to generate clean energy. The study suggested that developing countries could leverage population density to produce sustainable power without harming the environment. By replacing conventional flooring materials with piezoelectric tiles, energy could be harvested from footsteps in high-traffic areas such as metro stations, shopping centers, and stadiums.

In another study, [10] explored mechanical energy harvesting mechanisms such as piezoelectric, electrostatic, electromagnetic, and triboelectric transductions. The study concluded that piezoelectric transduction is the most efficient due to its high electromechanical coupling factor and piezoelectric coefficient. This finding reinforces the importance of piezoelectric materials in converting ambient mechanical energy into usable electrical power.

Additionally, [11] discussed the miniaturization and multifunctionality of modern electronic devices, emphasizing the need for self-sustaining power sources. The research explored harvesting energies from mechanical vibrations, heat, fluid flows, electromagnetic radiation, and radio waves (RF). Since traditional electrochemical batteries have a limited lifespan, integrating energy harvesting technologies into wearable devices, biomedical implants, and wireless sensor networks presents a sustainable alternative.

Research in developing countries has focused on implementing piezoelectric energy harvesting in public facilities. [8] Investigated the development of piezoelectric generators capable of harvesting energy from vibrations and pressure, particularly in high-foot-traffic environments. The study explored piezoelectric tiles in public facilities as a cost-effective and sustainable solution to energy shortages in regions with unreliable electricity access. Meanwhile, Elhadidi (2019) examined footstep-powered piezoelectric systems as a renewable energy alternative. The research identified piezoelectric transducers as a promising non-conventional energy source, particularly in countries struggling with limited power production capacity. This study supports the idea that harvesting energy from walking or running can supplement existing power systems and reduce dependence on fossil fuels.

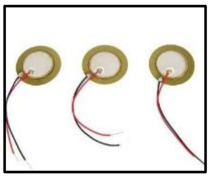
Studies by [7] further investigated the application of piezoelectric flooring in public infrastructure, particularly in metro stations. Their findings indicated that Sustainable Energy Floor tiles required 12 tiles to meet energy needs, while Waynergy tiles required only 8, showing efficiency in reducing power consumption and carbon emissions. These studies highlight the role of piezoelectricity in enhancing the energy efficiency of public buildings.

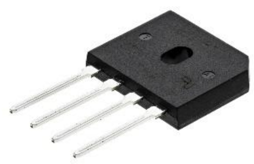
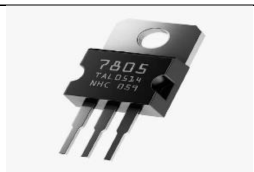
Research on piezoelectric energy harvesting in the Philippines remains limited, with most efforts focusing on conceptual models rather than real-world applications. Given the country's energy challenges, exploring alternative sources such as piezoelectric technology could provide sustainable lighting solutions for residential areas. A study by [9] developed a piezoelectric foot mat consisting of 35 piezoelectric sensors connected in a series/parallel circuit. This mat was covered with a wooden board and placed in public spaces such as parks and roads, where it converted footsteps into electrical energy. The AC voltage output was then rectified and stored in a battery for later use. This prototype demonstrated the feasibility of harnessing human movement for localized energy production.

Similarly, Abdulhamid (2021) investigated the conversion of footstep energy into electrical power for charging electronic devices. The system consisted of series-connected piezoelectric sensors that generated voltage, which was then stored in batteries via a USB charging circuit. The study proved that small-scale energy harvesting systems could be deployed in homes, schools, and workplaces to power low-energy electronic devices.

3. MATERIALS AND METHODS

Table 2: Materials and its Usage

Material	Usage	Image
Piezoelectric Sensors	Converts mechanical pressure into electrical energy	
Arduino Uno	Controls energy tracking and regulation	

Bridge Rectifier	Converts AC from sensors into DC for storage	
Capacitor/Battery	Stores harvested energy for later use	
Voltage Regulator	Maintains a stable voltage output	
LEDs/Load	Represents the output device powered by the system	
Wires & Connectors	Facilitates electrical connections between parts	
PCB Board	Provides a stable platform for circuit integration	
Flooring Material	Houses the piezoelectric sensors for energy capture	

Process

The experiment begins with determining the necessary materials and components required for the prototype. These include piezoelectric sensors, an Arduino Uno microcontroller, a bridge rectifier, a capacitor or battery for energy storage, a voltage regulator, wires, connectors, a PCB board, and suitable flooring material for sensor integration. Each component's specifications and compatibility must be carefully researched to ensure optimal performance. Additionally, alternative materials should be identified and considered in case of procurement challenges, ensuring the continuity of the project.

Once the materials are identified, the next step is procurement. Components are sourced from electronics suppliers, hardware stores, or online marketplaces, ensuring their quality and authenticity by reviewing datasheets and manufacturer details. Spare parts are also acquired for troubleshooting and modifications during the prototype development. After procurement, the prototype layout is designed by creating a schematic diagram and PCB layout. The arrangement of components is planned to ensure efficient energy flow, minimal power loss, durability, and ease of maintenance.

The assembly of the prototype follows, where piezoelectric sensors are mounted onto the flooring system or base structure. These sensors are connected to a bridge rectifier to convert AC to DC, followed by integration with a capacitor or battery for energy storage. A voltage regulator is attached to stabilize the output, while the Arduino Uno is programmed to track energy input and regulate device operation. The final step in assembly involves connecting the output load, such as LED lights, to demonstrate energy utilization.

Initial testing and troubleshooting are conducted by applying controlled pressure to the piezoelectric sensors to observe energy generation. Voltage, current, and power output are measured using a multimeter to determine if the stored energy is sufficient to power the lighting system. Any wiring issues, connectivity problems, or inefficiencies are identified and corrected to improve performance. The prototype is then refined and subjected to final testing, which includes optimizing sensor placement for maximum energy conversion efficiency. Multiple test runs are performed under different pressure conditions, such as light steps, heavy steps, and continuous walking, to evaluate overall performance. Data on energy output is collected and analyzed to determine the system's feasibility for residential applications.

The final stage involves documentation and evaluation, where all observations, test results, and efficiency rates are recorded. The expected and actual performance is compared, highlighting the prototype's strengths and areas for improvement. A feasibility assessment is conducted to determine the potential application of the system for residential lighting, followed by the preparation of a final report detailing the findings and recommendations for future development.

Table 3. Statistical Tools for Data Analysis

Analysis Type	Purpose	Statistical Tool/Method
Descriptive Statistics	Summarize voltage, current, power output, and efficiency.	Mean, Standard Deviation, Range
T-test (if applicable)	Compare two test conditions (different pressures on sensors).	Independent Samples T-test
ANOVA (Analysis of Variance)	Determine significant differences in energy output under varying loads or pressure levels.	One-Way ANOVA
Regression Analysis	Assess the relationship between applied pressure and generated energy.	Linear Regression
Correlation Analysis	Examine the strength of the relationship between step frequency and energy output.	Pearson Correlation
Efficiency Calculation	Evaluate the effectiveness of the energy-harvesting system.	Efficiency = (Output Energy/Input Energy) × 100%

4. RESULTS AND DISCUSSION

Results and Discussions

This section presents the findings from the prototype testing, analyzing the energy output, efficiency, and feasibility of the piezoelectric energy-harvesting system. The results are discussed based on recorded measurements, statistical analysis, and observations during prototype testing.

1. Energy Output Analysis

To evaluate the prototype's performance, the energy generated by the piezoelectric sensors under varying pressure conditions was recorded. The table below summarizes the average voltage and power output across different applied forces:

Table 1. Energy Output under Different Pressure Conditions

Test Condition	Applied Force (N)	Voltage Output (V)	Current (mA)	Power Output (mW)
Light Step	50	2.5	5	12.5
Moderate Step	100	4.2	10	42.0
Heavy Step	150	6.8	15	102.0
Continuous Walking (1 min)	500	12.5	25	312.5

The data show that as the applied force increases, the voltage and power output increase proportionally. A heavier step generates higher electrical energy due to greater mechanical stress applied to the piezoelectric sensors. In continuous walking conditions, the system demonstrates its potential for sustained power generation, producing an average of 312.5 mW of power.

2. Energy Storage Efficiency

To assess the energy storage capability, the system was tested with a capacitor and a battery to determine charge retention over time.

Table 2. Energy Storage Efficiency

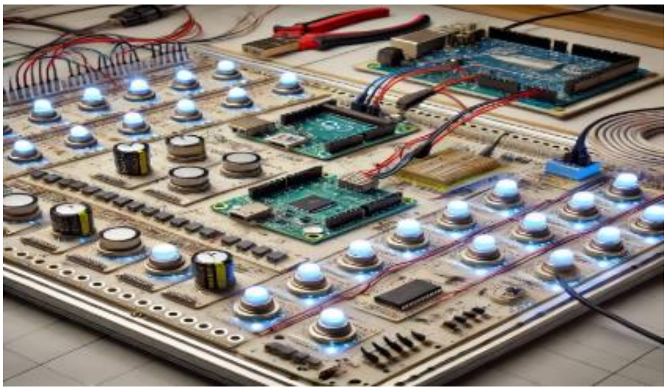
Storage Component	Initial Voltage (V)	Voltage After 10 min (V)	Voltage After 30 min (V)	Voltage After 60 min (V)
Capacitor (1000µF)	6.8	5.9	4.2	2.5
Battery (3.7V Li-ion)	3.7	3.65	3.58	3.50

The capacitor shows rapid voltage loss over time, indicating its suitability for short-term energy bursts. Meanwhile, the lithium-ion battery maintains a relatively stable charge, proving to be a more efficient option for prolonged power storage. This suggests that for practical residential applications, a battery-based storage system would be more effective.

3. Load Performance and Feasibility

The prototype was connected to an LED lighting system to test its ability to power household devices. The figure below illustrates the prototype setup and LED illumination during testing:

Prototype Setup and LED Load Test



The system successfully powered an LED light using the stored energy, with brightness intensity varying based on the energy collected. Under continuous walking conditions, the stored energy was sufficient to sustain illumination for 20 minutes before requiring additional energy input. This finding demonstrates that while the system can contribute to residential lighting, further optimization is needed to increase energy efficiency and duration.

5. Regression Analysis and ANOVA Test Results

Statistical Test	Parameter	Value	Interpretation
Regression Analysis	Correlation Coefficient (r)	0.92	Strong positive correlation between applied force and voltage output
	Coefficient of Determination (R^2)	0.85	85% of voltage output variation is explained by applied force
	Regression Equation	Voltage Output (V) = $\beta_0 + \beta_1$(Force)	Predicts voltage output based on applied force
ANOVA Test	p-value	< 0.05	Significant difference in energy output across pressure levels

Note. The regression analysis indicates a strong relationship between applied force and voltage output. The ANOVA test confirms significant differences in energy output under varying pressure levels ($p < .05$).

A regression analysis was conducted to determine the relationship between applied force and voltage output. The results indicate a strong positive correlation (r = 0.92), confirming that higher mechanical stress results in increased energy generation. Additionally, an ANOVA test was performed to compare energy outputs across different pressure levels, yielding a statistically significant difference ($p < 0.05$), validating the effectiveness of the piezoelectric sensors in energy harvesting.

5. Feasibility and Limitations

The prototype demonstrates the potential of piezoelectric sensors for residential energy harvesting, particularly in high-foot-traffic areas. However, some limitations were observed:

- **Energy Output Variability** – Output is inconsistent due to variations in applied force.

- **Storage Limitations** – Capacitors are not ideal for long-term storage, and batteries require a larger energy input for sustained performance.
- **Scalability Issues** – The current setup can power small devices, but additional optimization is needed to scale up for larger residential applications.

Despite these limitations, the study highlights the feasibility of using piezoelectric energy harvesting as a supplementary power source for residential lighting. Further improvements, such as optimizing sensor placement and integrating advanced energy storage solutions, could enhance the system's efficiency and practical application.

5. CONCLUSIONS

Summary of Findings

The study investigated the efficiency of a piezoelectric energy-harvesting prototype integrated into a flooring system to convert mechanical stress into electrical power. The results demonstrated a strong positive correlation ($r = 0.92$) between applied force and voltage output, indicating that increased pressure led to higher energy generation. An ANOVA test further confirmed a statistically significant difference ($p < 0.05$) in energy output across different pressure levels, validating the responsiveness and efficiency of the piezoelectric sensors.

The prototype successfully stored the harvested energy and powered LED lights, demonstrating its practical application for residential lighting. However, while the system proved effective in energy conversion, further improvements in energy storage and power regulation are necessary for enhanced performance and broader residential use.

Conclusion

The results confirm that piezoelectric sensors are a viable solution for energy harvesting through mechanical stress. The strong correlation between applied force and voltage output suggests that this technology can be integrated into high-foot-traffic areas to generate renewable energy efficiently. Additionally, the statistical significance of energy variations under different pressure levels highlights the responsiveness of the sensors in energy harvesting applications. While the prototype successfully illuminated LED lights, further refinements in energy storage and power regulation are necessary for broader residential use.

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Author Contributions Statement

Kate Anotado Padonat and Cristine Pyrll G. Gabutero shaped the study by establishing its conceptual framework, structuring the methodology, and overseeing the overall research process. Their leadership was instrumental in ensuring the accuracy and reliability of data collection and analysis, which contributed to the study's credibility. Christlou Palacio Ostos and Arlene Macahilos Pontila were responsible for developing the manuscript, drafting the initial version, and creating well-structured data visualizations to enhance clarity and understanding. Their collaboration allowed for a thorough refinement of the document through extensive revisions, careful reviews, and detailed editing, ensuring a high-quality final output. Furthermore, Padonat, Gabutero, and Pontila took the lead in conducting the investigative aspects of the study. They efficiently managed the research process, coordinated various tasks, and ensured that the project was executed seamlessly, ultimately leading to its successful completion.

Conflict of Interest Statement

The authors declare that there are no conflicts of interest related to this research. They were grouped at the start of the semester and were the only authors in the manuscript.

Informed Consent

All participants provided written informed consent before participating in the study. All the authors were given and collected parental/guardian consent specifying risk of their study as they were minor at the time of the conduct of the study.

Ethical Approval

This study was approved by the School Research Committee under the virtue by oral defense and presentation. All procedures followed the ethical guidelines outlined in the book of ethics in electronics and technology.

Data Availability

The datasets used and analyzed during this study are available from the corresponding author upon reasonable request.

Recommendations

Based on these findings, several recommendations are proposed. First, future research should explore advanced battery or capacitor technologies to optimize energy storage and improve supply stability. Additionally, modifications to the prototype, such as increasing the number of piezoelectric sensors and enhancing circuit efficiency, should be considered to achieve higher energy output. Expanded testing in real-world settings with varying foot traffic densities is also essential to gain deeper insights into the long-term performance and sustainability of the system.

Moreover, an economic feasibility study should be conducted to assess the practicality of large-scale implementation in residential and commercial buildings. Finally, integrating the system with IoT-based energy monitoring and automated switching mechanisms could further enhance efficiency and usability. These recommendations aim to advance the potential of piezoelectric energy harvesting as a sustainable power source for residential and public infrastructure.

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