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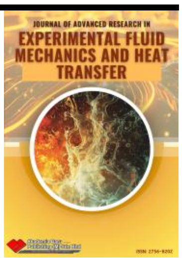

Experimental Validation of Piezoelectric Series Array Configuration for Energy Harvesting from Rainfall

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ABSTRACT

Harvesting energy using piezoelectric technology offers a promising method for generating renewable power from ambient environmental sources, such as rainfall. However, optimizing energy output from piezoelectric systems remains a challenge, particularly under varying weather conditions. This research specifically addresses the typical piezoelectric configurations in capturing energy from rainfall by examining the effectiveness of a series piezoelectric array configuration. For this purpose, a prototype system was designed, comprising square-shaped piezoelectric discs, AC to DC rectifiers, and a charge controller linked to a 12 V rechargeable battery. The system underwent testing under actual weather conditions over a period of seven months. Daily voltage output readings were recorded, revealing an increase from 11.0 V in November 2023 to 13.7 V in May 2024, corresponding to more intense rainfall events. The findings indicate that by optimizing piezoelectric array configurations, a potential 24.5% enhancement in energy capture efficiency can be achieved. This study demonstrates the viability of piezoelectric arrays for energy harvesting in regions with frequent rainfall and highlights possibilities for system improvements and integration with other renewable energy technologies. The insights provided by this research contribute to the advancement and optimization of practical piezoelectric energy harvesting applications.

Keywords:
Experimental validation; piezoelectric;
energy harvesting; rainfall

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1. Introduction

Globally, there is an increasing demand for sustainable energy generation methods. This is particularly significant for developing countries that have ample access to renewable resources, such as wind and solar power, and are not heavily dependent on conventional energy systems. As the costs of renewable energy technologies, like wind and solar, continue to decline, these countries are in a favorable position to swiftly adopt these systems [1]. Traditional energy sources, including coal, nuclear, and natural gas, utilize large synchronous generators to produce a stable AC electricity supply. However, due to environmental concerns and diminishing resource availability, these sources are gradually losing favor [2]. Consequently, there is a heightened focus on alternative energy sources that are both clean and reliable.

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Piezoelectric energy harvesting has emerged as an innovative technology capable of converting mechanical energy, such as vibrations and pressure, into electrical energy [3]. This process, known as the piezoelectric effect, occurs when specific materials generate electric charges in response to mechanical stress, such as bending or compressing [4,5]. Energy harvesting, often referred to as energy scavenging, involves capturing this otherwise wasted energy and transforming it into usable electricity, potentially reducing the reliance on batteries in numerous devices [6]. Piezoelectric materials have proven to be effective in harnessing energy from various sources, including vehicle vibrations, machinery, and human movements [7-9].

While many studies have focused on capturing energy from mechanical vibrations, recent research has ventured into harvesting energy from raindrop impacts, presenting a novel and relatively unexplored avenue for renewable energy generation. Rainfall is a plentiful natural resource, especially in tropical and temperate climates, providing an opportunity to harness kinetic energy in a way that has not been fully exploited [10]. Unlike traditional renewable energy sources like solar and wind, which are often limited by weather conditions and geographical constraints, rainfall can be consistent in specific regions, thus serving as a dependable power source. This innovative energy capture method employs piezoelectric materials to convert the mechanical energy of falling raindrops into electrical energy, offering an eco-friendly and sustainable solution for the energy needs of these regions.

For instance, Wang *et al.,* [11] developed a detailed model to elucidate the mechanisms by which electricity can be generated from the impact of raindrops on piezoelectric surfaces. Their research delved into the dynamics of droplet impact and how this kinetic energy can be converted into electrical power using piezoelectric transducers. The study's findings demonstrated that harvesting energy from raindrops could serve as a practical means to power small electronic devices, particularly in regions with frequent rainfall. Potential applications include environmental monitoring sensors, remote communication systems, and low-power wireless devices. The results suggest that in areas where solar or wind energy might be less effective due to cloudy conditions or insufficient wind, piezoelectric raindrop energy harvesting could provide a complementary or alternative renewable energy source. This breakthrough expands the prospects for renewable energy implementation, making it more accessible and feasible in diverse environmental settings, thus contributing to a more resilient and adaptive energy landscape.

Studies on piezoelectric energy harvesting have also tested various setups and energy sources, which help improve performance and reliability. Many of these studies have focused on sources like vibrations from people, bridges, or machines, using different configurations like single sensors or complex setups where sensors are arranged in various configuration arrays [12-15]. Unlike these complex configurations, pure series arrays like those used in this study are better suited for low-energy sources, such as rainfall.

Latest work utilized simulation software to explore how various piezoelectric array configurations could capture energy from raindrops [16]. The simulations indicated that certain configurations might be more efficient in converting kinetic energy into electricity. However, these findings were purely theoretical. To fully understand their performance, it is necessary to test these systems in real-world conditions, as factors such as varying raindrop sizes, changing environmental conditions, and material durability can significantly impact their performance [17,18]. One of the challenges is that simulation studies cannot entirely replicate the complexities of real-world conditions, making it difficult to accurately predict the practical efficacy of these piezoelectric systems. Furthermore, there is a need to optimize the electrical circuits, such as rectifiers and converters, to maximize the power output from piezoelectric devices. Recent studies have demonstrated that enhanced rectifier designs can substantially improve power output [19,20]. Therefore, field testing of these systems is crucial to ascertain their practical applications.

This paper presents the hardware setup and experimental results of piezoelectric systems designed to harvest energy from rainfall. Building on result from earlier simulations [16], the series piezoelectric array setup is chosen to see how well they work in real-life conditions. The voltage reading will be taken to provide a more complete picture of the system's potential. This work is necessary to fill the gaps to understand and validate the effectiveness of series array configuration optimized for harvesting intermittent energy from the unique rainfall pattern. This study could advance the field of renewable energy by providing practical insights into using piezoelectric systems for rainfall energy harvesting. By addressing the challenges of real-world implementation, this research could lead to new applications of piezoelectric technology, from self-powered sensors to sustainable energy systems for remote areas [21,22].

2. Methodology

The experiment utilized piezoelectric materials, specifically lead zirconate titanate (PZT) discs, known for their high piezoelectric coefficients and efficiency in energy harvesting applications [23]. For the experiment, the PZT discs were configured in series arrangement to evaluate their effectiveness in converting mechanical energy from raindrop impacts into electrical energy. This configuration was chosen based on promising result in the preliminary simulation studies using Proteus software [16].

2.1 Hardware Configuration

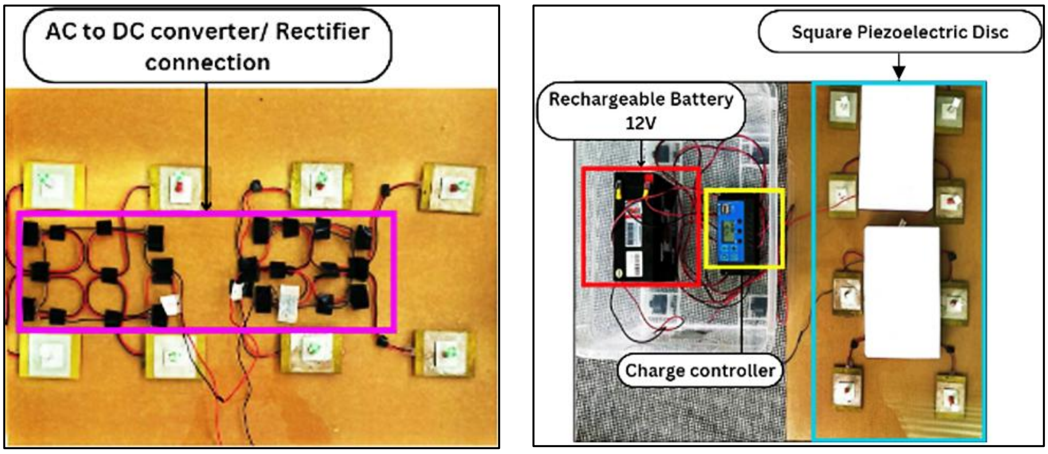
All components used in this experimental hardware setup are listed in the following Table 1. They include square piezoelectric discs, AC to DC converter, a rechargeable battery of 12V and a charge controller.

Table 1
Components used and their functions

Component	Function
Square piezoelectric discs	These are the main components for energy harvesting. When they experience mechanical stress, such as vibrations or pressure from raindrops, they generate an alternating current (AC) voltage.
AC to DC converter/Rectifier	These circuits convert the AC voltage generated by the piezoelectric discs into direct current (DC) voltage. Rectification is essential to store the energy in batteries or other storage devices.
Rechargeable battery (12V)	This battery stores the harvested energy. The use of a rechargeable battery allows for energy to be accumulated over time and then used as needed.
Charge controller	A charge controller is used to manage the charging of the battery. It prevents overcharging and ensures efficient energy storage, which is crucial for maintaining battery life and performance.

The square piezoelectric discs are arranged in a grid-like pattern. Based on Figure 1(a) below, two sets of piezoelectric arrays are set up. Each array has several discs connected in a specific configuration. The arrangement with eight discs is used to increase the amount of harvested energy. Each piezoelectric disc is wired to the AC to DC converter/rectifier circuits. The output from these discs is AC, so rectification is necessary before the current can be stored in the battery. The rectifier circuits are connected to the charge controller. The charge controller regulates the voltage and current to the battery, ensuring that the battery is charged efficiently without overcharging. Finally, the charge controller is connected to the 12V rechargeable battery, where the harvested energy is stored. This can be shown in Figure 1(b). This prototype demonstrates a practical application of piezoelectric energy harvesting from environmental mechanical stress. By converting mechanical energy into electrical energy, this setup shows the feasibility of using piezoelectric materials for renewable energy solutions.

For the data collection, only the reading at the voltage is being taken manually to monitor the immediate effect of raindrop harvesting to the prototype system. Environmental conditions, such as temperature and humidity, were not being monitored here so the effects of both condition to this study is ignored, thus being the limitation of the work. Moreover, factors such as wind and long-term wear and tear on materials could affect the performance of piezoelectric energy-harvesting systems in actual applications which are also became the limitations. Another limitation is the fabrication process for the piezoelectric arrays that involved manual assembly, which could introduce inconsistencies in material placement and alignment [24]. These practical constraints are basically being ignored for this early stage of experiment to focus on harvesting electricity from rainfall.



(a) (b)

Fig. 1. Hardware setup of piezoelectric system (a) Arrangement of 8 piezoelectric discs in series (b) Full connection of the prototype hardware

3. Results and Discussion

Table 2 indicates a generally positive trend in the voltage output over the observed period, which may suggest that the piezoelectric array configuration and associated components (like the rectifiers and charge controllers) are functioning optimally and are stable under varying conditions. The increase in voltage readings over time could be due to several factors, including environmental changes such as increased rainfall or vibrations, leading to more mechanical stress on the piezoelectric discs or seasonal effects where certain months have more favourable conditions (e.g., more rain), thus resulting in higher energy harvesting.

Table 2
Reading of voltage output between November 2023 to May 2024 (7 months)

Month	November 2023	December 2023	January 2024	February 2024	March 2024	April 2024	May 2024
Date	Voltage reading recorded (Vdc)						
1	11.0	11.4	11.9	12.4	12.4	12.5	13.1
2	11.0	11.3	11.9	12.4	12.4	12.5	13.1
3	11.0	11.3	11.8	12.4	12.4	12.6	13.1
4	11.1	11.3	11.8	12.4	12.4	12.6	13.1
5	11.0	11.3	11.8	12.4	12.4	12.6	13.2
6	11.0	11.4	11.8	12.4	12.4	12.6	13.2
7	11.0	11.4	11.9	12.4	12.4	12.7	13.2
8	11.1	11.4	11.9	12.4	12.4	12.7	13.3
9	11.1	11.4	11.9	12.4	12.4	12.8	13.3
10	11.1	11.4	11.9	12.4	12.4	12.8	13.4
11	11.2	11.4	12.0	12.4	12.4	12.8	13.3
12	11.1	11.4	12.0	12.4	12.4	12.9	13.4
13	11.1	11.5	12.1	12.4	12.4	12.9	13.4
14	11.1	11.5	12.1	12.4	12.4	12.9	13.4
15	11.1	11.4	12.1	12.4	12.4	12.9	13.4
16	11.2	11.4	12.2	12.4	12.4	12.9	13.4
17	11.2	11.4	12.1	12.4	12.4	12.9	13.4
18	11.2	11.5	12.2	12.4	12.4	12.9	13.5
19	11.2	11.5	12.2	12.4	12.4	12.9	13.5
20	11.2	11.5	12.2	12.4	12.4	12.9	13.5
21	11.2	11.6	12.2	12.4	12.4	13.0	13.5
22	11.3	11.6	12.3	12.4	12.5	13.0	13.6
23	11.3	11.7	12.3	12.4	12.5	12.9	13.6
24	11.3	11.7	12.3	12.4	12.5	13.0	13.6
25	11.3	11.8	12.3	12.4	12.5	13.0	13.6
26	11.3	11.8	12.4	12.4	12.5	13.0	13.6
27	11.3	11.8	12.3	12.4	12.5	13.0	13.7
28	11.3	11.9	12.4	12.4	12.5	13.0	13.7
29	11.4	11.9	12.4	12.4	12.5	13.1	13.7
30	11.4	11.9	12.4	-	12.5	13.1	13.7
31	-	11.9	12.4	-	12.5	-	13.7

3.1 Correlation Analysis Between Weather Data and Voltage Readings

Based on the weather data [25] provided for 2023 and 2024 as illustrate in Figure 2, the correlation between weather patterns and the voltage readings from the piezoelectric energy harvesting system can be analysed. The weather data includes various conditions such as drizzle, light rain, moderate rain, heavy rain, and thunderstorms. These conditions are represented by different colours, and their frequency over time can help to better understand the variations in voltage readings.

The weather data graph shows varying intensities of rainfall throughout the year, with notable periods of moderate to heavy rain and thunderstorms. From November to December 2023, the main weather events observed are light and moderate rain, shown in green shades. Drizzle is frequent, particularly around late November and early December. From January to February 2024, rain (both light and moderate) remains the dominant weather, with more frequent events than in previous months. Fog appears consistently, especially in the early hours, indicating potentially cooler and humid mornings. There are drizzle and occasional sleet appear. From March to May 2024, it shows an increase in diverse weather events, including light to heavy rain and thunderstorms. Heavy rain (dark green) and thunderstorms (orange) are more frequent, suggesting a more unstable weather pattern, possibly due to seasonal changes. Overall, rain especially light and heavy rain is a consistent weather event that would be great opportunities for this project.

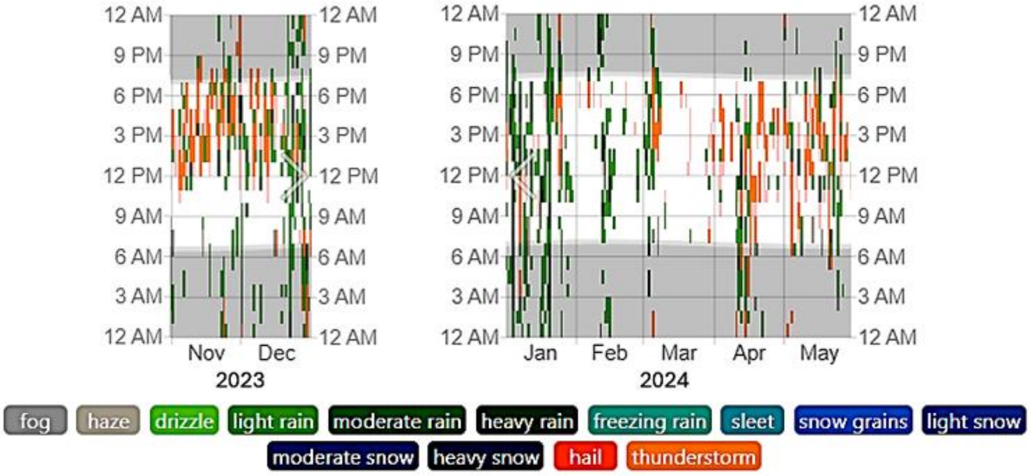


Fig. 2. Weather data from November 2023 until May 2024

3.1.1 Relating weather to voltage readings

The voltage readings from the piezoelectric system remain relatively stable in November and December 2023, ranging from 11.0 V to 11.9 V. During this period, the weather data shows moderate rain, which could provide consistent mechanical stress on the piezoelectric discs, resulting in stable voltage readings. In January 2024, there is an increase in rainfall intensity with moderate to heavy rain, which correlates with a gradual increase in voltage from 11.4 V to 12.4 V. This indicates that higher rainfall intensity improves the energy harvested from the piezoelectric discs due to increased mechanical vibrations. From March to May 2024, the voltage readings stabilize around 12.4 V in March, which coincides with the presence of light to moderate rain. However, in April and May, the voltage readings increase to 13.1 V and 13.7 V, respectively. During these months, there is a higher density of moderate rain and thunderstorms, providing more significant mechanical stress, which further boosts energy output.

The daily variations in voltage readings throughout the monitored months exhibit a direct correlation with changes in weather patterns. Days characterized by heavy rainfall or thunderstorms tend to generate higher voltage outputs, attributed to the increased vibrations and mechanical stress exerted on the piezoelectric discs. The data analysis indicates that rainfall intensity and frequency are pivotal factors influencing the performance of the piezoelectric energy harvesting system. Higher rainfall intensity and frequent occurrences result in more substantial mechanical vibrations, thereby enhancing the system's voltage output. Notably, the system demonstrates improved performance during months with more intense and frequent rainfall events, such as January, April, and May 2024. Conversely, periods with lighter or less frequent rainfall, like March 2024, show stable yet lower voltage outputs.

These results reveal a strong correlation between weather patterns and the voltage output of the piezoelectric energy harvesting system. Rainfall intensity, particularly moderate to heavy rain and thunderstorms, significantly impacts system performance. This information is crucial for optimizing the system further and predicting its energy output under varying weather conditions. Future work may involve developing predictive models to estimate energy output based on weather forecasts or exploring adaptive configurations that dynamically respond to environmental changes. The recorded voltage readings indicate that the piezoelectric energy harvesting system is stable and capable of consistent long-term performance. There is a noticeable improvement in voltage output from November 2023 to May 2024, reflecting effective energy harvesting and the potential for hardware configuration optimization.

Future studies could focus on a more detailed correlation analysis between specific environmental conditions, such as rainfall intensity and frequency, and voltage output to enhance system optimization. Additionally, refining the piezoelectric array configuration or exploring alternative materials may result in further performance enhancements

4. Conclusions

Based on the experimental results and analysis of the piezoelectric energy harvesting system, it is evident that the system's efficiency in generating electrical energy from rainfall is influenced by various factors, including the intensity and frequency of rain. The voltage output readings recorded over several months indicate a gradual increase in voltage levels, particularly from March 2024 onwards, correlating with the weather patterns showing heavier rainfall. This demonstrates the potential of using piezoelectric arrays for sustainable energy generation in regions with consistent rainfall. However, to improve the system's performance, enhancements such as optimizing the piezoelectric array configuration, incorporating more efficient rectifiers, and using advanced charge controllers can be considered. Additionally, integrating this system with other renewable energy sources, such as solar, could create a hybrid solution that maximizes energy harvesting under varying weather conditions, thereby providing a more stable and reliable power supply for practical applications.

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