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LAKWABOT: HARNESSING KINETIC ENERGY FROM FOOTSTEP AS A POTENTIAL RENEWABLE ENERGY SOURCE TO SMARTPHONES

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ABSTRACT

This study investigates the potential of harnessing kinetic energy from footsteps as a renewable energy source for smartphones. With the rising demand for electricity, particularly for mobile devices, there is a pressing and growing need for sustainable and environmentally friendly alternatives. The research focuses on the development of LakwaBot, an innovative energy-harvesting tile embedded with piezoelectric sensors that convert mechanical energy from footsteps into usable electrical energy. A quantitative comparative-experimental research design was used to assess LakwaBot's efficiency by measuring the electricity generated from varying step counts (100, 500, and 1000 steps) and its ability to effectively charge a smartphone battery. Data were collected through controlled and consistent trials and analyzed using statistical methods, including a paired t-test, to evaluate the significance of differences between the energy stored and the battery capacity charged. The results showed that as the number of footsteps increased, both the electricity stored and the battery capacity charged also increased correspondingly. However, the overall energy output remained relatively low, indicating that further advancements and improvements in piezoelectric technology and energy storage systems are required. The findings highlight the potential of kinetic energy harvesting in modern urban infrastructure and its alignment with long-term sustainability goals and clean energy initiatives. Future research should focus on optimizing piezoelectric sensors and energy conversion to enhance efficiency.

Keywords: *kinetic energy harvesting, piezoelectric sensors, renewable energy, smartphone charging, sustainable technology*

INTRODUCTION

A city deprived of energy was akin to a cell without mitochondria, halting essential processes that made life easier. However, in the real world, the pursuit of convenience is often detrimental to the planet. Electricity had become essential in powering most technologies, including smartphones, which relied on batteries for energy—thus creating a need to regenerate their power over time. Globally, the mobile industry uses a significant amount of energy, consuming 1% of worldwide energy. While this might have seemed small, it was more than the energy produced by all coal-fired power plants in the United Kingdom, which contributed significantly to climate change (Astrom, 2014). Despite various efforts, the increasing energy consumption by smartphones remained unresolved. This served as an eye-opener, emphasizing the need to conduct the study, as it played a vital role in finding solutions to reduce energy demand in the mobile industry and its environmental impact.

The increasing smartphone usage increased energy consumption since the country relied heavily on non-renewable power sources. The Philippines ranked 11th globally in 2023, with 69.66 million smartphone users (Degenhard, 2024). This number was projected to rise by 35.9 million users, representing a 41.96% growth from that figure by 2029 (Balita, 2024). The study aimed to investigate the potential of energy-harvesting tiles using piezoelectric (PZT) sensors to convert kinetic energy from footsteps into a renewable energy source for smartphones, particularly in urban environments. A piezoelectric material generates an electrical charge when subjected to mechanical stress (Khun, 2018). The study aimed to contribute to a more sustainable society by harnessing kinetic energy from footsteps.

Alternative energy sources have been explored, such as the study by Roy et al. (2021), which innovated energy-generating shoes that utilized piezoelectric (PZT) sensors to convert kinetic energy from footsteps into renewable energy for portable chargers. Furthermore, Dalisay et al. (2024) investigated using PZT in energy-harvesting staircases to generate light from footsteps. Like those studies, the researchers aimed to explore energy solutions that could be integrated into everyday environments, aligning with the Philippine Department of Energy's mission (RA 7638) to ensure a stable, affordable, and environmentally sound energy supply. The study also corresponded to the Renewable Energy Act of 2008 (RA 9513) and the Energy Efficiency and Conservation Act of 2019 (RA 11285), which supported and mandated renewable energy development and energy-efficient technologies.

The practical use of PZT materials embedded in tiles in urban infrastructures—like hallways and pavements—where stored energy could charge smartphones remained relatively unexplored. The study filled this research gap by designing and evaluating energy-harvesting tiles embedded with piezoelectric sensors. Its findings could contribute to the body of knowledge on energy-harvesting technologies while advancing sustainable energy systems in urban infrastructures.

Therefore, the study's primary objective was to design and evaluate energy-harvesting tiles embedded with piezoelectric sensors aimed at converting the kinetic energy of footsteps into electrical energy, particularly by integrating them in public spaces. By demonstrating the feasibility of piezoelectric tiles as a potential energy source, the study could help address global energy challenges and promote the adoption of environmentally friendly technologies in schools and other public areas.

RESEARCH QUESTIONS

This study aimed to assess the potential of LakwaBot as a kinetic energy harvesting device, specifically the Piezoelectric tile, within urban environments, emphasizing the development of a sustainable society powered by renewable energy sources. Specifically, this study answered the following questions:

1. What is the amount of energy stored by LakwaBot as a kinetic energy harvesting device in terms of:
    1.1 100 steps;
    1.2 500 steps; and
    1.3 1000 steps?
2. What battery capacity can be charged on a smartphone using the electricity stored by LakwaBot as the kinetic energy harvesting device in terms of:

2.1 100 steps;
2.2 500 steps; and
2.3 1000 steps?

3. Is there a significant difference in the efficiency of LakwaBot as the kinetic energy harvesting device between the electricity stored and the resulting battery capacity of a smartphone?

HYPOTHESIS

There is no significant difference in the efficiency of LakwaBot as the kinetic energy harvesting device between the number of steps and the resulting battery capacity of a smartphone.

LITERATURE REVIEW

Kinetic Energy Harvesting Process

Kinetic energy harvesting is converting mechanical energy, such as that generated by human or ambient movement, into electrical energy, often through piezoelectric materials that produce electricity when pressure is applied (Hussain, 2023). This technology holds promising applications in urban environments, where kinetic pavements capture energy from pedestrian traffic to power local devices like streetlights and data transmission systems (Pavegen, 2023). Additionally, piezoelectric sensors are specially designed floor tiles that harness energy from human footsteps, providing a renewable energy source that complements other urban energy solutions (Aslam et al., 2023).

Expanding on this innovative approach, Manlapig (2023) explored the development of energy-generating shoes to investigate portable energy solutions further. The benefits of kinetic energy harvesting include the potential for reducing reliance on non-renewable energy sources, minimizing urban carbon footprints, and providing a sustainable solution for powering low-energy devices. However, challenges persist. Chakraborty (2023) notes that high installation costs and low energy output compared to conventional sources limit its scalability.

Moreover, other studies emphasize that improving the efficiency and durability of piezoelectric materials is crucial for making this technology viable for widespread use (Ahmed et al., 2023). While kinetic energy harvesting presents a promising avenue for sustainable energy, ongoing research and development are essential to overcome these challenges and fully realize its potential.

Piezoelectric Technology

Piezoelectric technology relies on materials such as crystals and ceramics that generate electric charges when subjected to mechanical stress (Britannica, 2023). This phenomenon occurs due to the displacement of electric dipoles within the material, leading to charge accumulation. When stress is applied, these materials convert mechanical energy into electrical energy (ScienceDirect, 2023). The mechanism behind piezoelectric materials involves the alignment of electric dipoles, which creates a potential difference and results in the generation of electric charge (Matsusada, 2023). This energy conversion is influenced by the properties of the material and the degree of applied stress. Piezoelectric devices, including sensors, actuators, and ultrasonic transducers, are commonly found in everyday applications such as lighters, microphones, and medical imaging (Sekhar et al., 2023).

This versatility has also led to significant developments in energy harvesting devices. Piezoelectric materials are increasingly used in low-power applications, such as wearable electronics and smart sensors (Selim et al., 2023). Energy harvesting through piezoelectricity is gaining attention, particularly in systems designed to generate power from foot traffic using piezoelectric sensors (Helonde et al., 2023). However, durability, cost, and efficiency challenges persist, necessitating further research for large-scale implementation (Yadav et al., 2018). Despite these obstacles, piezoelectric technology holds significant potential for contributing to renewable energy solutions, showcasing its promise in advancing sustainable practices (American Piezo, 2023).

Renewable Energy Sources

The planet possesses significant features that benefit humanity in many aspects of life, including resources that can be harnessed as a source of electricity. This is the essence of renewable energy sources, which refer to alternative energy that is both endless and readily available (United Nations, 2024; EDF, 2024). Sustainable energy, such as kinetic energy, has been extensively studied and implemented worldwide, as it is abundant and widely accessible (Ang, 2020). Popular forms of kinetic energy harvesting include solar, wind, hydro, tidal, geothermal, and biomass energy (Active Kinetic, 2024).

The development of kinetic energy aims to provide safe, clean, secure, and affordable energy (Ang, 2020). Converting wasted ambient kinetic energy into usable electrical energy supports self-sustaining devices like wearable technology and smart sensors, which can function without frequent battery replacements (Chen et al., 2022). Kinetic energy can also be harvested from everyday human activities, like walking and running, using electromagnetic, piezoelectric, and triboelectric energy harvesting technologies (Wang et al., 2022).

Building on this foundation, kinetic energy harvesting has been widely adopted to mitigate environmental damage from non-renewable energy sources, reducing reliance on fossil fuels and helping to lower carbon emissions. Additionally, generating kinetic energy in urban areas is decentralized, enhancing energy resilience and reliability. It encourages active transportation and healthier lifestyles by motivating walking and cycling. This realization fosters environmental responsibility and community engagement (Prasad, 2023).

Moreover, renewable energy sources can reduce energy costs over time, particularly solar and wind energy, which have seen significant price declines, making them increasingly competitive with traditional energy sources. These advancements collectively emphasize the impact of kinetic energy harvesting on sustainable energy practices and improving environmental health.

METHODOLOGY

RESEARCH DESIGN

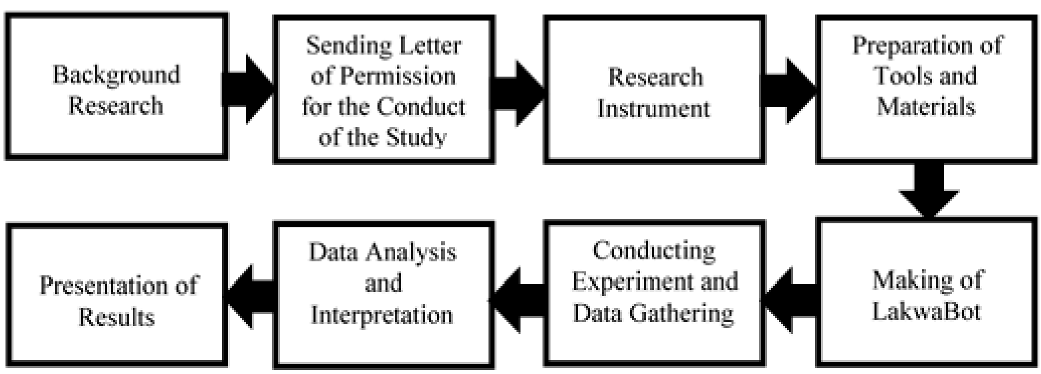
This quantitative study used a comparative-experimental research design involving data collection and experimentation to gather detailed information. According to Annenberg Learner (2024), a comparative observational study examined measurement differences across treatment categories. This study applied various treatments to scales that captured kinetic energy from footsteps, with electrical output measured in voltage and current. Additionally, a paired T-test was used to assess whether there was a significant difference between the treatment results. JMP Statistical Discovery (2024) noted that the paired t-test was commonly used when there were paired measurements, and the aim was to determine whether the mean difference between these paired measurements was significantly different from zero. This study aimed to evaluate the potential of LakwaBot to maximize energy production, contributing to the optimization of kinetic energy from footsteps as a renewable energy source for smartphones.

RESEARCH INSTRUMENTS

The researchers developed an observation guide to collect data on the potential of harnessing kinetic energy from footsteps as a renewable energy source. The observation guide included two tables, each designed to capture specific data. Table 1 records the amount of electricity stored by LakwaBot based on three categories of footsteps: 100, 500, and 1000 steps. Table 2 measured the battery capacity that could be charged on a smartphone using the electricity stored by the device, also categorized into 100, 500, and 1000 steps. By utilizing these observation guides, the researchers assessed the efficiency of LakwaBot and gathered data that provided valuable insights into its practical application for generating renewable energy from footsteps.

DATA GATHERING PROCEDURE

The data-gathering process began with obtaining permission from the homeowner to experiment. After receiving approval, the researchers prepared the necessary tools and materials and constructed LakwaBot by embedding piezoelectric sensors into the tiles. Throughout the process, proper safety precautions were taken to ensure the safety of both the researchers and the surrounding environment. The experiment was then conducted, measuring the voltage from footsteps and the corresponding battery capacity it could charge on a smartphone. Data on electricity produced and stored were collected using the developed observation guide and analyzed using a statistical method to identify the significant difference between the number of steps, energy produced, and battery capacity. To ensure transparency and the reliability of the results, all data were carefully documented, and any assumptions or limitations were clearly stated. Finally, the results were analyzed, interpreted, and presented, with conclusions drawn regarding the feasibility of integrating this technology into smartphone applications.



DATA ANALYSIS

This study aimed to analyze the electricity stored by LakwaBot and the corresponding battery capacity that could be charged on a smartphone. Additionally, it sought to investigate whether there was a significant difference in the device's efficiency based on the number of steps and the resulting battery capacity. To address these research questions and provide a comprehensive analysis of the data, the following statistical procedures were applied:

Mean. The mean, or average, was computed to determine the central tendency of the data. It was used to represent the overall performance or outcome of the LakwaBot in terms of electricity stored and battery capacity charged. The formula for calculating the mean is:

$$\bar{x} = \frac{\sum x_i}{n}$$

Where:
$\bar{x}$ = Mean
$\sum x_i$ = sum of all the data points
n = total number of the data points

Standard Deviation. The standard deviation, the square root of the variance, was calculated to quantify the amount of variation or spread in the dataset. A higher standard deviation indicated more significant variability, while a lower standard deviation suggested that the data points were closer to the mean.

$$\sigma = \sqrt{\frac{\sum(x_i - \mu)^2}{N}}$$

Where:
σ = Population Standard Deviation
N = size of the population
x_i = each value from the population
μ = population mean

Paired T-Test. The paired t-test was applied to compare the means of paired measurements and answer the problem's third statement. This statistical method assessed whether there was a statistically significant difference between the electricity stored and the resulting battery capacity to determine the efficiency of LakwaBot. The paired t-test was used in this study, where the null hypothesis posited that the mean difference between the paired measurements was zero, and the alternative hypothesis suggested that the mean difference was significantly different from zero. The formula for the t-statistic in a paired t-test was:

$$t = \frac{\sum d}{\sqrt{\frac{n(\sum d^2) - (\sum d)^2}{n - 1}}}$$

Where:
d = Difference per paired value
n = Number of Samples

If the calculated P-value does not exceed the critical value from the t-distribution table, the null hypothesis is rejected, indicating that there is a significant difference between the paired measurements.

Table 1.
The Amount of Energy Stored by LakwaBot

Range (Ah)	Description	Verbal Interpretation
0 - 0.2	Very Low	The amount of electricity stored by LakwaBot is insufficient.

0.21 - 0.4	Low	The amount of electricity stored by LakwaBot is minimal.
0.41 - 0.6	Moderate	The amount of electricity stored by LakwaBot is adequate.
0.61 - 0.8	High	The amount of electricity stored by LakwaBot is good.
0.81 and above	Very High	The amount of electricity stored by LakwaBot is excellent.

Table 2.
The Amount of Energy Stored by LakwaBot

Range (mAh)	Description	Verbal Interpretation
0-40	Very Low	The battery capacity charged by LakwaBot is poor.
41-80	Low	The battery capacity charged by LakwaBot is insubstantial.
81-120	Moderate	The battery capacity charged by LakwaBot is adequate.
121-160	High	The battery capacity charged by LakwaBot is good.
161 and above	Very High	The battery capacity charged by LakwaBot is excellent.

ETHICAL CONSIDERATION

The researchers ensured that the study posed no harm to anyone involved. In doing so, the researchers carefully considered the following ethical principles:

Authority. The researchers sought approval from relevant authorities and institutional bodies, ensuring that the study adhered to ethical guidelines and was conducted under proper oversight.

Deceit. Complete transparency was maintained throughout the study. The purpose, procedures, and potential risks associated with the research were clearly outlined. No information was withheld, misrepresented, or distorted in any way.

Falsification. The research team maintained integrity by reporting all data truthfully. No data was altered or fabricated to achieve desired outcomes, ensuring the study's reliability and credibility.

Plagiarism. The researchers ensured originality by conducting their experiments and citing all external sources properly. They accurately acknowledged any references to previous studies or ideas from other authors, eliminating any risk of plagiarism.

Risk. Potential risks to the researchers, such as physical strain from energy-generating activities, were minimized by implementing proper safety precautions and closely monitoring their well-being throughout the study.

Benefits. The study aimed to provide a renewable energy solution for smartphones, benefiting users and the environment
students).

RESULTS AND DISCUSSION

Table 3.
Average Electricity Stored by LakwaBot

Number of Steps	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean	Description
100 (Ah)	0.231	0.234	0.230	0.231	0.233	0.232	**Low**
500 (Ah)	0.324	0.281	0.297	0.291	0.294	0.297	**Low**
1000 (Ah)	0.433	0.435	0.452	0.434	0.432	0.433	**Moderate**

Table 3 shows the average electricity stored by LakwaBot across three step categories: 100, 500, and 1000 steps. For 100 steps, the mean electricity stored is 0.232 Ah, indicating a low range and suggesting insufficient electricity stored. As the number of steps increases, the mean electricity stored at 500 steps rises to 0.297 Ah; however, it still falls within the low range, indicating insufficient storage capacity. Furthermore, for 1000 steps, the mean electricity stored increases to 0.433 Ah, reaching a moderate range, yet it still reflects minimal electricity stored in the battery. These results demonstrate that while the electricity stored by LakwaBot increases with the number of steps, the overall output remains low to moderate. This implies that despite improved efficiency with more steps, the energy harvested remains insufficient for substantial practical applications.

The findings align with previous studies on kinetic energy harvesting devices. For example, the study by Sarala et al. (2020) highlighted the challenges in generating substantial electricity using piezoelectric technology, noting that while energy is harvested, the amounts are generally low. Similarly, the study by Dalisay et al. (2024) emphasized that while kinetic energy harvesting through piezoelectric sensors is a promising technology, the actual energy output tends to be minimal, particularly in small-scale applications. These studies support the current study's findings and highlight the need for further advancements in piezoelectric technology to enhance energy output and efficiency, making it a more practical renewable energy solution for charging smartphones and other low-power devices.

Table 4.
Average Battery Capacity Generated by LakwaBot

Number of Steps	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean	Description

100 (Ah)	0.231	0.234	0.230	0.231	0.233	0.232	**Low**
500 (Ah)	0.324	0.281	0.297	0.291	0.294	0.297	**Low**
1000 (Ah)	0.433	0.435	0.452	0.434	0.432	0.433	**Moderate**

Table 4 shows the average battery capacity generated by LakwaBot across three different step categories: 100, 500, and 1000 steps. For 100 steps, the mean battery capacity generated is 81.13 mAh, indicating a moderate capacity level, suggesting that the resulting capacity is adequate. As the number of steps increases, the mean battery capacity at 500 steps rises to 104.09 mAh, which, while still within the moderate range, represents an adequate increase in capacity. Furthermore, for 1000 steps, the mean battery capacity increases further to 153.02 mAh, reflecting a high battery capacity when charged. These results demonstrate that although the battery capacity generated by LakwaBot increases with the number of steps, the overall output remains moderate to high. This implies that, despite the device becoming more efficient with more steps, the energy harvested may still not be sufficient for substantial practical applications.

The findings align with previous studies on kinetic energy harvesting devices. For example, the study by Chen et al. (2022) reviewed the potential of kinetic energy harvesting for loT systems, highlighting the challenges in generating substantial electricity using piezoelectric technology. They noted that while energy is harvested, the amounts are generally low to moderate, similar to the findings of this study.

Ang et al. (2020) also discussed the fundamentals and applications of kinetic energy harvesting from sustainable sources, emphasizing the need for further technological advancements to enhance energy output and efficiency. These references support the current study's findings and highlight the need for further advancements in piezoelectric technology to enhance energy output and efficiency, making it a more practical renewable energy solution for charging smartphones and other low-power devices.

Table 5.
Average Battery Capacity Generated by LakwaBot

Pair	Mean Diff.	t	df	Sig. (2-tailed)
Pair 1*	-80.90	-299.92	4	<.001
Pair 1**	-103.79	-41.46	4	<.001
Pair 1***	-152.58	-117.10	4	<.001

***ElectrictyStored 100; BatteryCapacity100**
****ElectrictyStored500; BatteryCapacity500**
*****ElectrictyStored1000; BatteryCapacity1000**

Table 5 shows the results of the paired sample t-test comparing the electricity stored and the battery capacity across three step categories: 100, 500, and 1000 steps. The table provides each pair's mean differences, standard deviations, t-values, degrees of freedom, and significance levels. For 100 steps, the mean difference is -80.90, with a t-value of -299.92 and a significance level of less than 0.001. Similarly, for 500 steps, the mean difference is -103.79, the t-value is -41.46, and the significance level remains below 0.001. At 1000 steps, the mean difference is -152.58, with a t-value of -117.10, and the significance level again falls below 0.001. These results reveal a statistically significant difference between each step category's electricity stored and battery capacity. The consistently negative mean differences across all three step categories indicate that the electricity stored is consistently lower than the battery capacity charged, highlighting a substantial gap between the two.

The findings of this study are consistent with previous research on kinetic energy harvesting devices. Related studies found that while technologies like piezoelectric sensors can convert kinetic energy into electricity, the overall output remains low, highlighting the challenges of achieving substantial power generation in small-scale applications (Manlapig, 2023; Helonde et al., 2023). Ang et al. (2020) also emphasized the limitations in energy output from piezoelectric systems and the potential for technological advancements to improve efficiency. These studies reinforce the need for further improvements in piezoelectric technology to enhance energy output and make it a more viable solution for powering low-power devices like smartphones.

RESULTS AND DISCUSSION

This study aimed to assess the potential of LakwaBot, a kinetic energy harvesting device utilizing piezoelectric tiles, in converting footsteps into electrical energy for smartphone charging. Specifically, it examined the amount of electricity stored by LakwaBot for varying step counts, the corresponding charge transferred to a smartphone battery, and the statistical significance of the relationship between foot traffic and energy conversion.

This study employed a comparative-experimental research design, using a paired t-test to analyze differences in energy generation before and after foot traffic was applied. The study was conducted at Oringo Subdivision, Barangay City Heights, General Santos City, using a prototype embedded with piezoelectric sensors. Data collection involved controlled footstep applications to measure energy output and charging capability.

1. **Electricity Stored in Every Step of LakwaBot**. The researchers found that the number of footsteps exerted on the piezoelectric tile directly impacts the voltage charged to the rechargeable battery. As the number of footsteps increases, more voltage is generated, and the ampere-hour (Ah) stored in the battery also rises. The average electricity stored in the battery is 0.232 Ah for 100 steps, 0.297 Ah for 500 steps, and 0.433 Ah for 1000 steps. Overall, the electricity stored in the battery remains relatively low to moderate.

2. **Battery Capacity Generated in Every Number of Steps of LakwaBot.** The researchers discovered that the resulting battery capacity is directly proportional to the number of footsteps. The mean battery capacity charged in a smartphone is 81.93 mAh for 100 steps, 104.90 mAh for 500 steps, and 153.02 mAh for 1000 steps. Overall, the battery capacity charged in the smartphone is generally moderate to high.

3. **Significant Difference Between Electricity Stored and Battery Capacity.** The researchers found a significant difference between the electricity stored and the battery capacity charged, as the p-value for every pair is lower than the significance threshold of 0.05. This indicates that as the electricity stored increases, the battery capacity charged in the smartphone also increases.

CONCLUSIONS/RECOMMENDATIONS

The study demonstrated that LakwaBot effectively converted kinetic energy from footsteps into electrical energy, reinforcing its potential as a renewable energy source for applications such as smartphone charging. However, the current energy output remained limited, highlighting the need for advancements in piezoelectric technology and energy storage to improve efficiency. Integrating kinetic energy harvesting into urban infrastructure supported sustainability initiatives and aligned with the Philippine Department of Energy's objectives to promote alternative and renewable energy solutions. Potential applications of this technology included public spaces, transportation hubs, and educational institutions, where high foot traffic could be utilized for energy generation.

The findings of this study suggested that while LakwaBot offered a promising approach to harnessing renewable energy, further research and development were necessary. The researchers observed that adding more piezoelectric sensors and optimizing energy conversion mechanisms, such as using a full bridge rectifier to convert the alternating current from the piezoelectric sensors to direct current, were crucial for improving its overall performance. These advancements contribute to the broader adoption of kinetic energy harvesting technology in sustainable urban development.

POLICY RECOMMENDATIONS

Urban planners and government agencies should consider integrating kinetic energy harvesting technology into walkways, transit stations, and public spaces where high foot traffic can generate electricity. Implementing pilot projects would allow for assessing large-scale feasibility and optimizing energy storage solutions, contributing to a more sustainable and energy-efficient urban environment.

Technology developers and engineers are encouraged to focus on enhancing the efficiency of piezoelectric tiles by utilizing advanced materials and developing improved energy storage systems. These developments can help improve the practicality and effectiveness of kinetic energy harvesting in various applications.

RESEARCH RECOMMENDATIONS

Educational institutions should incorporate kinetic energy harvesting research into STEM programs to promote awareness and encourage innovation among students. Conducting prototype testing within schools and universities can provide valuable insights into the technology's performance and inspire future developments in renewable energy. Hands-on research initiatives can also contribute to refining and improving piezoelectric energy harvesting systems.

The Department of Energy should support funding initiatives for renewable energy research, particularly piezoelectric applications. Collaboration with universities, research institutions, and private industries can facilitate the development of scalable energy-harvesting projects. Strengthening partnerships between the government and the private sector will help accelerate advancements in kinetic energy technology and expand its potential applications in the country's energy infrastructure.

Future researchers could investigate other factors that may influence the efficiency of piezoelectric sensors, such as weight, distance, and pressure. Moreover, the number of piezoelectric sensors should be considered when developing more advanced piezoelectric tiles.

Future studies should explore optimizing sensor placement, material selection, and circuit design for greater efficiency. This could lead to optimizing piezoelectric sensors as energy-harvesting devices, improving their efficiency and sustainability.

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