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Are triboelectric nanogenerators more efficient than piezoelectric transducers in generating energy from precipitation?

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Abstract
This review examines two primary methods for harvesting energy from precipitation: triboelectric nanogenerators (TENGs) and piezoelectric transducers, which are leading technologies in converting mechanical energy from rain into electrical energy. The comparison between TENGs and piezoelectric transducers focuses on their operational mechanisms, material characteristics, and environmental factors such as water pH and temperature. The review highlights that TENGs offer greater design flexibility, efficiency in low-intensity rain, and cost-effectiveness, while piezoelectric transducers excel in high-frequency environments. The development of hybrid systems combining both technologies presents a more efficient and sustainable solution for rain energy harvesting.

1 Introduction

Every moment a raindrop falls, a sustainable energy source is harnessed by harvesting its power. Sustainable technology development has placed energy harvesting from environmental sources at the forefront, giving potential solutions for decentralized energy networks and workable substitutes for traditional power sources (Whulanza et al., 2020.). Triboelectric nanogenerators (TENGs) and piezoelectric transducers have become the leading methods for harvesting energy from precipitation events, such as rainfall (Lu et al., 2021). While both methodologies leverage distinct material and structural properties, the fundamental question arises: Are triboelectric nanogenerators more efficient than piezoelectric transducers in generating energy from precipitation? This review delves into the mechanisms underlying these technologies, from the tribo-charging phenomenon when water interacts with solid surfaces to the specific materials employed in device design. The influence of various water properties, such as pH and temperature, should be considered on the efficiency of energy generation. By comparing triboelectric and piezoelectric systems' energy outputs and practical applications under similar rainfall conditions, this paper aims to compare these technologies.

The ancient Greeks and Romans utilized energy from rain through the use of water wheels to mill grain and refine wool in cloth making (Fearon, 2020). Scientists have used that same principle for large energy generation projects such as dams (Moran et al., 2018). Piezoelectric power has been used for decades, though triboelectric generators have recently become more widely used. Harnessing energy from precipitation is a sustainable alternative to fossil fuels in generating energy (Wang et al., 2023). It is also a suitable energy source for communities that lack other resources, particularly those in regions with limited sunlight or wind. However, there is debate regarding whether piezoelectric or triboelectric is more efficient.

Triboelectric nanogenerators (TENG) use the triboelectric charges and the polarization of a dielectric to change mechanical energies from precipitation into electrical energies (Zhu et al., 2020). This can be further generalized by utilizing the strong triboelectric properties of materials; all polymers, such as PTFE, PDMS, and PVDF, when used with conductive metals aluminium or copper, are efficient in transformational energy under rain (Zhang & Olin, 2020). This strategy broadens to renewable energy sources and offers a sustainable way to exploit natural precipitation. This strategic coupling of such materials maximizes electrical output. It ensures effectiveness with TENGs under various environmental conditions- a major step towards exploiting previously unexploited natural resources for power generation (Gao et al., 2023).

Piezoelectric transducers operate based on the piezoelectric effect, which occurs when some materials generate an electric charge in response to mechanical stress, and this energy is employed in turning precipitation into electrical energy (Meng et al., 2022). Environmental energy, such as that from rainfall, reverberates with these piezoelectric transducers and turns into electrical power. Some of the critical piezoelectric transducers involve high piezoelectric coefficient polymers such as polyvinylidene fluoride (PVDF) and ceramics with high piezoelectric coefficients such as lead zirconate titanate (PZT) (Piezoelectricity - an Overview | ScienceDirect Topics, 2013.). Piezoelectric technology stands out for its unique ability to convert rain and other untapped mechanical energies into usable power. This feature positions it distinctively in renewable energy, offering high-source energy and low-power solutions for sensory devices or small, remote applications (Covaci & Gontean, 2020).

2 Materials and Method

This literature review is based on papers found through Google Scholar and Hollis.

The search terms used were generating energy from ("rain" OR "precipitation") using a "triboelectric" nanogenerator and using a "piezoelectric" transducer. Papers that were published before 2010 were excluded. Exclusions were also made based on the relevance of the abstract, as some results did not focus on triboelectric or piezoelectric power generation. The chosen papers ranged from literature reviews to original research to ensure a wide and specific selection of information. In total, 7 literature reviews and 29 original research articles were selected.

3 Results and Discussion

Comparative Efficiencies

Comparative efficiency is a crucial factor in determining the practical application and scalability of the TENG and Piezoelectric transducers. Both technologies' efficiency varies significantly due to their distinct operating principles and material characteristics. TENGs use the triboelectric effect and are more efficient in scenarios with predominant low-frequency mechanical energy (Cheng et al., 2023). This is due to TENGs' ability to effectively convert the sporadic and variable force of falling raindrops into electrical energy, which makes them a highly suitable technology for rain energy harvesting. Moreover, TENGs' ability to operate in low-speed precipitation conditions, such as light rain or drizzle, is an advantage as it can maintain its consistent performance across various rainfall intensities (Liu et al., 2019).

On the other hand, piezoelectric transducers, which convert mechanical energy into electricity, tend to have higher efficiency in environments with high-frequency mechanical vibrations (Li et al., 2018). The impact of the movement of the raindrop onto the piezoelectric materials generates vibration, which is then converted into electricity by these devices. Piezoelectric materials with a high piezoelectric coefficient and an application-specific design can lead to more efficient energy conversion. However, these factors can also contribute to increased costs and complexity in the manufacturing process, which might not be worth the expense considering the energy output (Chang et al., 2010).

Comparing the technical aspects of these two technologies, TENGs offer the advantage of material flexibility, as they can be constructed from a wide range of materials, including cost-effective and sustainable options (Zhang & Olin, 2020). This versatility gives TENGs the benefit of being more flexible for various applications and allows for design optimisation to enhance efficiency. Moreover, the operational mechanism of TENGs is simple, making it easier to integrate them into current systems and structures (Zhao et al., 2022).

Despite the technological difference, it is important to recognise other factors to take into account when applying both systems for harvesting energy from precipitation. Although one of the biggest factors is their absolute efficiency, it does not guarantee an optimised performance in every application. The usefulness of TENGs and piezoelectric transducers depends on several factors, including the materials' durability, ease of integration into various settings, and the system's total cost (Wang et al., 2015; Jing & Kar-Narayan, 2018). Consequently, because of their adaptability, affordability, and ability to function in a wide range of environments, TENGs present a strong substitute for piezoelectric transducers, even though piezoelectric may offer a higher energy output in certain situations (Han et al., 2019).

Precipitation

The influence of water properties, such as pH and temperature, on the efficiency of energy generation through rain harvesting technologies, is a broad topic that intersects with the comparison between TENG and piezoelectric transducers. The water's pH, temperature, and density could influence the efficiency of TENGs in rainwater energy harvesting, as these properties affect the water's conductivity and the surface charge density of the materials (Cui et al., 2022). A study on high-output piezo/triboelectric hybrid generators highlighted that integrating piezoelectric generators into TENG produces higher output power, indicating a potential influence of water properties on hybrid generator performance (Jung et al., 2015; Wang et al., 2015).

Piezoelectric transducers, on the other hand, convert mechanical stress applied by raindrops into electrical energy through the piezoelectric effect (Viola et al., 2014.). The efficiency of piezoelectric transducers could also vary with water's pH and temperature, as these could affect the mechanical properties of the piezoelectric materials and, consequently, their electrical output (Wang et al., 2022). A study on multifunctional flexible piezo/triboelectric hybrid water energy harvesters based on biocompatible materials demonstrated enhanced performance under different water sources, including raindrops, showcasing the adaptability of piezoelectric transducers to environmental conditions (Mariello et al., 2021).

Comparing both technologies, TENGs are generally more adaptable to various mechanical energy forms, including low-speed water drops, due to their mechanism of operation, which does not rely on material deformation (Shen et al., 2023). This adaptability might make TENGs more effective in varied pH and temperature conditions, especially when considering hybrid systems that combine piezoelectric and triboelectric effects for enhanced energy harvesting from rainwater. With their reliance on material deformation to generate electricity, Piezoelectric transducers might exhibit more sensitivity to environmental conditions affecting the mechanical properties of piezoelectric materials (Lay et al., 2021). However, advancements in material science, particularly the development of flexible and biocompatible piezoelectric materials, are expanding the efficiency and applicability of piezoelectric transducers in energy harvesting from rain under diverse environmental conditions (Covaci & Gontean, 2020). Regardless, both technologies have advantages and limitations, but innovative hybrid approaches and material advancements can be optimised for effective rainwater energy harvesting under varying environmental conditions. The future of rain energy harvesting lies in the continuous improvement of these technologies and their adaptability to the dynamic properties of water.

Applications

TENGs, known for efficiently converting the kinetic energy from falling raindrops into electrical energy, are ideal for integration into outdoor structures such as rooftops, umbrellas, and raincoats(Tang et al., 2020). These applications can provide a sustainable power source for outdoor electronic devices, environmental monitoring stations, or even remote sensors in agricultural fields where rainwater is abundant. By harnessing the power of precipitation, these devices can operate independently of traditional power grids, reducing dependency on fossil fuels and promoting renewable energy sources (Wang et al., 2015).

On the other hand, piezoelectric transducers, which excel in converting mechanical vibrations into electrical energy, can be applied to capture the energy from rain impact on surfaces like windows or specially designed kinetic energy harvesters (Viola et al.,2021). The vibrational energy generated by raindrops hitting these surfaces can be transformed into electricity, powering sensor networks for weather monitoring or small electronic devices. This method is particularly advantageous in regions experiencing frequent rainfall, where it can contribute significantly to the energy mix of sustainable urban infrastructure, enhancing energy efficiency and sustainability (Chang et al., 2010).

Developing hybrid systems that combine the strengths of TENGs and piezoelectric transducers presents an even more compelling approach to rain energy harvesting. Such systems can optimise energy capture from both the kinetic energy of raindrops and the vibrational energy of their impact, ensuring a consistent power supply under varying weather conditions(Palomba et al., 2022). This hybrid approach maximises the energy harvesting efficiency from rain and provides a versatile solution adaptable to different surfaces and scales, from individual wearable devices to large-scale architectural implementations (Jing & Kar-Narayan, 2018).

In wearable technology, for instance, embedding TENGs and piezoelectric materials into outdoor clothing and accessories can create garments that generate power from every raindrop, charging mobile devices or powering integrated LED lighting for safety and visibility (Pu et al., 2023). This application not only showcases the potential of harvesting energy from rain in our daily lives but also highlights the synergy between innovative energy solutions and functional design, driving forward the integration of renewable energy technologies into the fabric of society literally and figuratively (Guo et al., 2018).

4 Conclusion

After thoroughly evaluating both TENGs and piezoelectric transducers, it can be concluded that TENGs hold more potential for rainwater energy harvesting. Based on the overall efficiency and the response to various water properties, TENGs show better efficiency and responds compared to piezoelectric. Additionally, TENGs have better flexibility in materials that could be used for sustainability and cost-effective devices than piezoelectric transducers. While both technologies have their strengths and weaknesses, TENG's effectiveness and adaptiveness puts it in a pivotal position in the future landscape of renewable energy technologies. The journey towards a sustainable energy future is complex and challenging. However, technology is developing closer to realizing a world powered by renewable energy through continued research and development in technologies like TENGs and piezoelectric transducers. In the future, it is crucial to enhance the efficiency of both TENG and piezoelectric transducers by creating innovative designs and integrating both technologies into a hybrid system. Moreover, this renewable energy solution should be implemented into more designs, infrastructure, and wearable technologies to make this Earth more sustainable.

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