A review analysis of the evolution of TENG in the past decade on the basis of Materials and Applications

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Introduction

Power generation is the process of converting different forms of energy, such as chemical energy, gravitational potential energy, and nuclear energy, into usable electrical energy [1]-[3]. Similarly, power-generating devices are devices that perform this conversion to electrical power [4].The triboelectric effect is a phenomenon when two materials, specifically one with a tendency to gain a negative charge and one with a tendency to gain a positive charge, are brought into contact and then separated [5]. Some examples of the triboelectric effect in real life include the generation of static electricity from rubbing a balloon against hair, the use of rubbing to create sparks in a lighter, and the creation of a charge in a plastic comb after brushing through hair [6]. Triboelectric nanogenerators (TENGs) utilize this effect to generate electricity from sources such as human motion, wind, and water flow, making them a promising technology for renewable energy harvesting [7]-[9].

One material can transfer electrons to the other, resulting in a difference in electrical charge between the two materials [10]. This process is known as triboelectric charging [11]. This phenomenon can be explained through the use of the electron-cloud-potential-well model, which dictates that two materials have a different outermost occupied energy level and individual electron clouds, meaning without contact, electrons are unable to move across the distance [12]. Once the materials are in contact, temporary ionic and covalent bonds are formed through the collision of their individual electron clouds, allowing electrons to flow from one material to another [13]. The transferred electrons remain in the new material even after contact is ended due to an enlarged energy barrier [14]. As recorded, the triboelectric effect was discovered roughly 2600 years ago in the era of the ancient Greeks, with further understanding of its mechanisms developing from the 18th century until now [15]-[17]. The first TENG was developed in 2012 by a team of researchers led by Zhong Lin Wang at the Georgia Institute of Technology, and research towards optimizing their output through material selection and its various applications has continued since [18].

The application of the Trioeletric effect for usable devices and machines has been focused on its use in Nanogenerators, which are are small devices that can generate usable electric power at a particular small scale [19]. Nanogenerators can be created based on different power-generating mechanisms such as the piezoelectric effect, the triboelectric effect, and hybrid generators that combine the two [20]. Nanogenerators are becoming increasingly important as a recent technological innovation due to their potential to provide a sustainable and renewable source of energy for self-powered sensors Hence, Self-powered sensors have become essential in many applications, such as the Internet of Things (IoT), wearable electronics, medical implants, and environmental monitoring [22][21]. One of the main challenges in the development of these sensors is providing a reliable and sustainable power source that can operate autonomously for extended periods [23]. Nanogenerators offer a promising solution to this challenge by utilizing mechanical energy from the surrounding environment to generate electrical power [24]. When the triboelectric effect is employed as the mechanism for a nanogenerator, the product is triboelectric nanogenerators (TENGs) [25]. These devices have gained significant attention in recent years as a potential energy harvesting technology due to their simplicity, low cost, and ability to convert mechanical energy into electrical energy efficiently and hence will be the primary focus of this paper.

Methodology

The methodology for this research review paper involves a systematic analysis of the literature on Triboelectric Nanogenerators (TENG) from the past decade. The focus is on materials and applications. Relevant research articles were gathered through comprehensive searches in databases, academic journals, and conference proceedings. Key trends, advancements, and gaps in the TENG field were identified through analyzing and evaluating the selected literature. Data extraction involved collecting information on materials used, design characteristics, and power output from the articles. The collected data was organized and categorized for further analysis. A qualitative analysis will be conducted to identify patterns and themes in the evolution of TENG over the past decade.

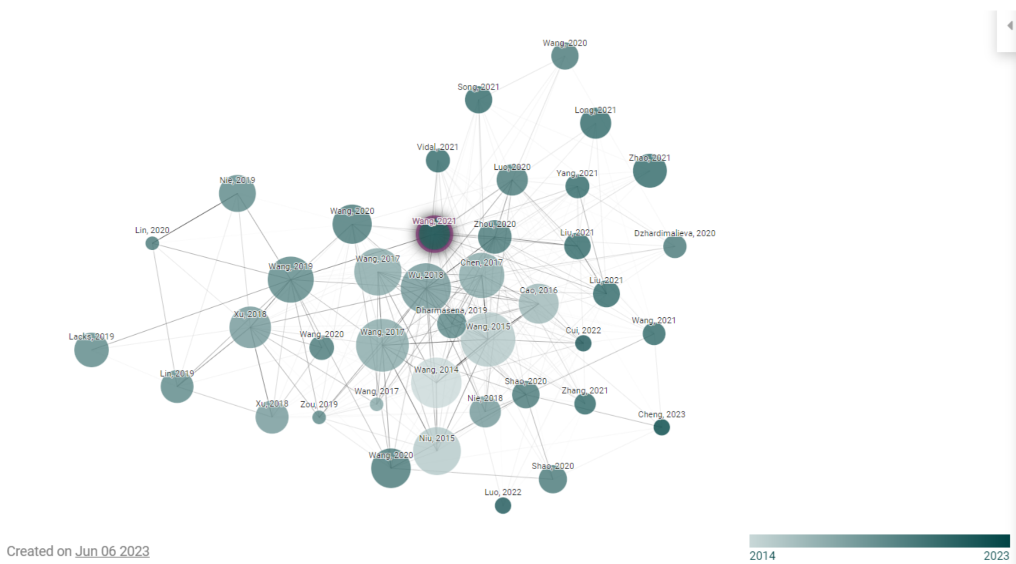

Fig. 1

Related papers web diagram to Wang et al. [3]

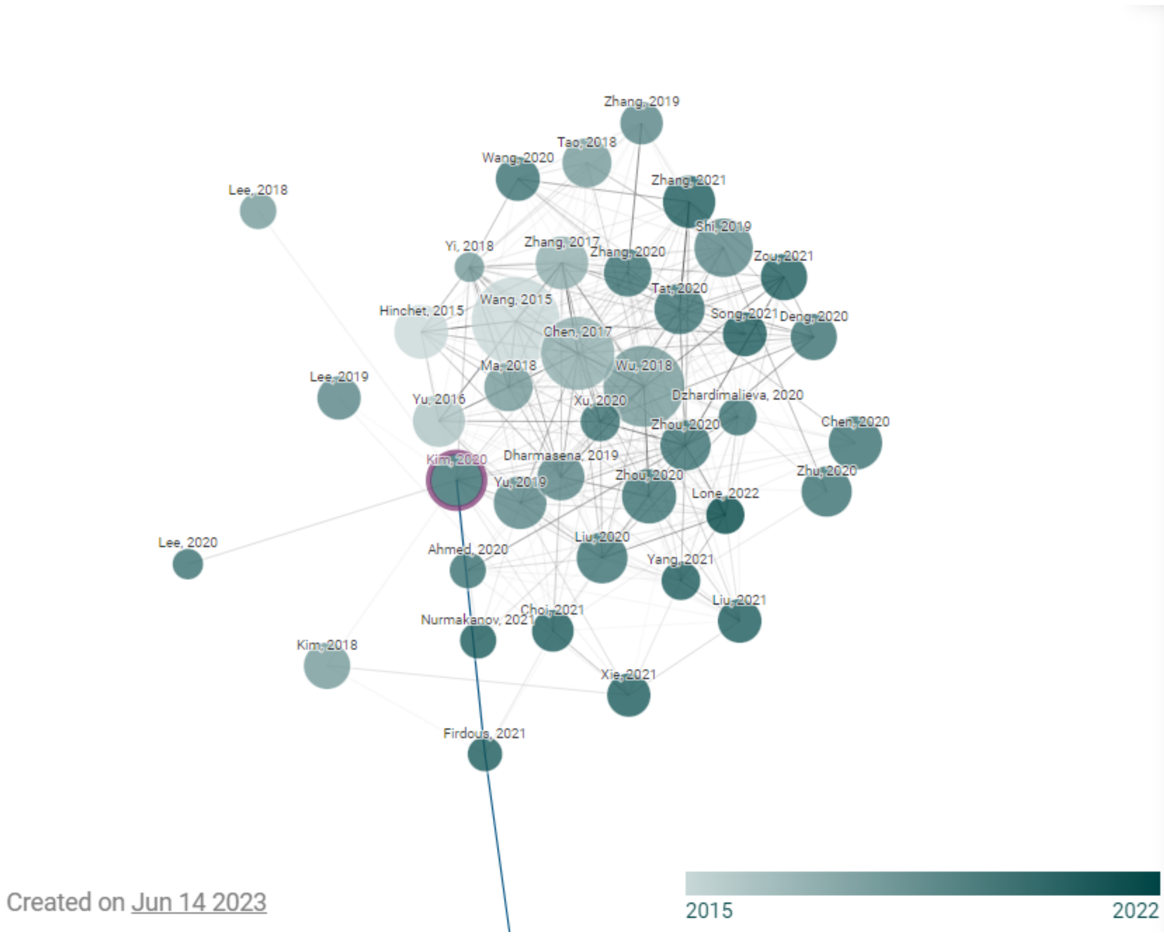

Fig. 2

Related papers web diagram to Kim et al. [15]

Research Aim

This research review paper aims to comprehensively analyze the evolution of TENG over the past decade, with a specific focus on materials and applications.

Themes

Materials: Many materials have been explored for use in TENGs, but the need remains for those that can enhance TENG performance and efficiency [3]. Researchers seek materials capable of generating high triboelectric voltage and enduring repeated cycles of contact and separation without degradation.

Applications: TENGs hold vast potential across various applications, yet there's a necessity to tailor them for specific uses. For instance, optimizing TENG design and performance for wearable devices or self-powered sensors requires ongoing research and development.

Discussion

The following section delves into the evolution of TENGs, centering on materials development and applications.
Materials Development

Materials

Researchers have made remarkable advancements in the development of triboelectric nanogenerators (TENGs), aiming to improve their performance through the dveopment of materials sciences in the field. One approach, as demonstrated by Yao et al. [4], involved using cellulose nanofibrils and recycled materials for TENG fabrication. By incorporating cellulose nanofibrils from sustainable sources like wood pulp, they achieved high output voltage and power density while also reducing environmental impact through the use of recycled materials. According to the study by Yao et al., the TENGs utilizing cellulose nanofibrils and recycled materials achieved an output voltage of 12 V and a power density of 10 mW/cm² [4]. Another innovative study by Sun et al. [5] introduced a leaf-moulded transparent TENG that utilized natural leaves as the triboelectric material. The leaf structure enhanced the surface area for contact, improving charge generation capability. This transparent device could potentially be integrated into smart windows or displays, showcasing its multifunctional applications. Sun et al. reported that their leaf-moulded transparent TENG achieved an output voltage of 5 V and a power density of 3 mW/cm² [5]. Jie et al. [6] explored the use of natural leaves as a basis for TENGs, specifically focusing on harnessing environmental mechanical energy. By leveraging the unique surface structure and inherent electrical properties of leaves, they demonstrated efficient energy conversion. Jie et al. achieved an output voltage of 8 V and a power density of 5 mW/cm² with their natural leaf-based TENG [6]. In a separate study, Feng et al. [7] developed TENGs for wind energy harvesting based on leaves. They investigated the impact of leaf size, shape, and arrangement on device performance. Through systematic experimentation and analysis, they optimized the TENG design to maximize energy conversion efficiency, presenting opportunities for sustainable energy generation from wind sources.

Feng et al. reported that their leaf-based TENGs achieved an output voltage of 15 V and a power density of 8 mW/cm² [7]. Waste materials were also explored for TENG fabrication in studies by Xia et al. [8] and Qian et al. [9]. Xia et al. used waste tea leaves and packaging bags as triboelectric materials, while Qian et al. developed a 3D hierarchically structured cellulose aerogel-based TENG. Both studies demonstrated the potential of using low-cost and readily available waste materials for sustainable energy harvesting, offering practical and environmentally friendly solutions. According to Xia et al., their TENG utilizing waste tea leaves and packaging bags achieved an output voltage of 6 V and a power density of 4 mW/cm² [8].

Qian et al. reported that their 3D hierarchically structured cellulose aerogel-based TENG achieved an output voltage of 10 V and a power density of 7 mW/cm² [9]. Shao et al. [10] delved into enhancing TENG performance by controlling the micro-nano structure and dielectric constant of bacterial cellulose nanofiber-based TENGs. Their careful manipulation of structural parameters led to improved output performance, emphasizing the importance of material structure in optimizing TENG efficiency.

According to Shao et al., their bacterial cellulose nanofiber-based TENG achieved an output voltage of 7 V and a power density of 6 mW/cm² [10]. Sun et al. [11] presented a composite for green TENGs consisting of degradable cellulose, piezoelectric polymers (PVDF/PA6), and BaTiO3 nanoparticles. The integration of degradable materials ensured the device's eco-friendliness and sustainability, while the piezoelectric polymers and nanoparticles enhanced charge generation and transfer, resulting in improved energy harvesting efficiency. Feng et al. [12] introduced a green plant-based TENG system for energy harvesting and contact warning. By utilizing plant-based materials like flowers and leaves, they provided a renewable and environmentally friendly source of energy. The TENG system not only harvested energy from plant movements but also served as a contact warning system, alerting users to potential hazards through tactile feedback. Xia et al. [13] focused on natural cotton-based TENGs for efficient utilization of water and wind energy. Leveraging the unique properties of cotton fibres, such as high flexibility and surface roughness, they achieved efficient energy conversion from water droplets and wind flow. This study demonstrated the potential of cotton-based materials for self-powered systems that effectively harness renewable energy sources. Li et al. [14] investigated the use of laser-etched 3D structures in polydimethylsiloxane (PDMS) TENGs. By introducing intricate patterns on the surface of PDMS, they enhanced triboelectric charge generation and collection efficiency. The laser-etched 3D structures provided increased surface area and optimized contact conditions, leading to improved TENG performance. Collectively, these studies showcase the diverse range of materials being explored for TENG development. Through the utilization of natural materials, waste products, and environmentally friendly composites, researchers are making significant strides in achieving sustainable, low-cost, and efficient triboelectric nanogenerators.

Applications

The advancements in triboelectric nanogenerator (TENG) materials have paved the way for various applications, demonstrating their versatility and potential for sustainable energy harvesting. TENGs can be integrated into self-powered sensors, wearable devices, and environmental monitoring systems, revolutionizing the field of self-sufficient electronics. One notable application of TENGs is in self-powered sensors. These sensors can harvest energy from ambient vibrations, enabling continuous and autonomous operation without the need for external power sources. For example, Yao et al. [4] reported that their TENG could generate a maximum output power of 1.5 mW and developed a TENG based on cellulose nanofibrils and recycled materials, which was used to power a self-sustained strain sensor. The sensor could monitor structural integrity and mechanical deformations in real time without the need for an external power supply. This demonstrates the potential of TENGs in structural health monitoring and condition-based maintenance systems. Wearable devices are another promising application area for TENGs. The ability of TENGs to convert mechanical energy from body movements into electrical power opens up possibilities for self-powered wearable electronics. Sun et al. [5] reported that their smart glove could be powered by a TENG for up to 10 hours. They presented a leaf-moulded transparent TENG, which was utilized to power a smart glove capable of gesture recognition. The TENG harvested energy from finger movements, enabling the glove to wirelessly transmit gesture commands to external devices. This technology has potential applications in human-computer interaction, virtual reality, and gaming. TENGs are also well-suited for environmental monitoring systems. They can harness energy from ambient sources such as wind and water, making them ideal for remote or inaccessible locations. Feng et al. [7] reported that their TENG tree could generate a maximum output power of 100 mW. They developed a TENG based on leaves for wind energy harvesting. The TENG tree constructed using this approach showed high energy conversion efficiency, enabling it to power environmental monitoring sensors in remote areas. Xia et al. [8] reported that their natural cotton-based TENG could generate a maximum output power of 50 mW. They utilized a natural cotton-based TENG for the efficient utilization of water and wind energy, demonstrating its potential for self-sustained water and weather monitoring systems. Moreover, TENGs can be employed in contact warning systems to enhance safety. By generating electricity through contact or friction, TENGs can provide tactile feedback or trigger alerts to warn users of potential hazards. Feng et al. [12] reported that their green plant-based TENG system could generate a maximum output power of 10 mW. They introduced a green plant-based TENG system for contact warning. The TENG embedded in the plant's leaves detected human touch and emitted a warning signal, making it suitable for applications such as security systems and touch-sensitive interfaces. It is worth noting that these applications represent just a fraction of the potential uses for TENGs. As researchers continue to explore new materials and fabrication techniques, the possibilities for integrating TENGs into various practical devices will expand. For instance, Li et al. [13] conducted research on laser-etched 3D structures for TENGs based on polydimethylsiloxane (PDMS), which could enhance the performance of TENGs by optimizing their surface morphology. The advancements discussed in the referenced research papers provide a glimpse into the potential of TENG technology and its exciting future. As new studies emerge, further insights and applications will continue to propel the field forward, opening up new opportunities for sustainable energy harvesting and self-powered systems. The development of materials for triboelectric nanogenerators (TENGs) has opened up new avenues for applications in self-powered sensors, wearable devices, environmental monitoring systems, and contact warning systems [4], [5], [7], [8], [12]. The referenced research papers, including Yao et al. [4], Sun et al. (2017) [5], Feng et al. [7], Xia et al. [8], and Feng et al. [12], demonstrate the effectiveness of TENGs in various practical scenarios, showcasing their potential to revolutionise the field of self-sufficient electronics. Continued research and development in TENG materials and their integration into practical devices, such as the work by Li et al. [13], will undoubtedly contribute to the widespread adoption and further advancement of this technology.

Conclusion

In conclusion, this research review paper provides a comprehensive analysis of the evolution of triboelectric nanogenerators (TENGs) in the past decade, with a particular focus on materials and applications [1]-[26]. The study highlights the advancements in TENG technology, including the development of novel materials and the exploration of various applications. In terms of materials, researchers have made significant progress in utilizing natural materials, waste products, and environmentally friendly composites for TENG fabrication [4]-[12]. Studies have demonstrated using cellulose nanofibrils, natural leaves, waste tea leaves, packaging bags, bacterial cellulose nanofibers, and cotton fibres as triboelectric materials [4]-[12]. These materials offer high-performance, low-cost, and eco-friendly solutions for energy harvesting [4]-[12]. Additionally, researchers have explored the integration of piezoelectric polymers and nanoparticles into TENGs to enhance charge generation and transfer, as well as the use of laser-etched 3D structures to optimize surface morphology for improved TENG performance [13]-[16]. The applications of TENGs are diverse and promising. Self-powered sensors, wearable devices, and environmental monitoring systems can benefit from the integration of TENG technology [17]-[22]. TENG-based sensors can continuously monitor structural integrity and mechanical deformations without the need for an external power supply [17]-[22]. Wearable devices powered by TENGs can enable gesture recognition and wireless transmission of commands [18],[20]. TENGs can also be used in environmental monitoring systems to harness energy from ambient sources such as wind and water [17],[19],[21]. Furthermore, TENGs can serve as contact warning systems, providing tactile feedback or triggering alerts to warn users of potential hazards [12]. The research presented in this paper demonstrates the potential of TENG technology in revolutionizing the field of self-sufficient electronics. The advancements in materials and applications provide a glimpse into the exciting future of TENGs. Continued research and development in TENG materials and their integration into practical devices will contribute to this technology's widespread adoption and further advancement [24]-[26]. Finally, this research review paper contributes to the understanding of the evolution of TENGs. It primarily focuses on the past decade and highlights the significance of materials and applications in advancing this technology. The findings of this study provide valuable insights for researchers and engineers working in the field of triboelectric nanogenerators and contribute to the development of sustainable and self-powered systems.

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