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| RESEARCH ARTICLE

Triboelectric Nanogenerators for Sustainable Environmental Remediation: A Comprehensive Review

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| ABSTRACT

This review highlights the extensive applications of triboelectric nanogenerators (TENGs) in environmental remediation, such as water treatment, air purification, soil remediation, and waste management. TENGs harvest mechanical energy from ambient sources and convert it into electrical energy through the triboelectric effect, offering a sustainable solution to self-powered environmental systems. Recent advances in materials, particularly biopolymers and nanocomposites, have significantly enhanced energy conversion efficiency and eco-friendliness. Despite their promise, challenges such as material limitations, efficiency issues, and scalability remain. This review emphasizes the importance of interdisciplinary collaboration and innovation in overcoming these challenges and realizing the full potential of TENGs in addressing critical global environmental issues.

| KEYWORDS:

Triboelectric nanogenerators, environmental remediation, sustainable energy, water treatment, self-powered systems

| ARTICLE INFORMATION

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1. Introduction

The increasing demand of the sustainable technology to overcome environmental pollution and energy shortage has drawn great attention to triboelectric nanogenerators (TENGs), which have proved to be an ideal candidate for tackling these serious challenges[4]. TENGs can harvest ambient mechanical energy (e.g. vibrations, waves, and human motion) into electricity using the triboelectric effect, providing a low-cost and self-powered method for various environmental applications [12].

Recent studies have demonstrated the use of TENGs in driving the electrochemical degradation of pollutants [1], the recovery of valuable materials from waste streams [2][3], and real-time monitoring of groundwater pollution in agricultural settings [4]. These applications show the potential of TENGs to power environmental remediation processes without relying on conventional energy sources.

Although TENGs have much promise, they have major obstacles. Energy conversion remains inefficient; the materials employed often lack long-term stability, particularly under severe conditions [6][7]. Furthermore, their integration with current environmental treatment systems, such electrochemical and photocatalytic technologies, stays underdeveloped and raises technical challenges[8][9].

This work intends to investigate not only the present advancement in the application of TENGs in environmental cleanup but also the future directions. By reviewing recent developments, spotting important constraints, and evaluating possibilities for innovation in materials and system integration, this work aims to provide insights into how TENG-based technologies can support more sustainable and self-powered environmental solutions.

2. Fundamentals of Triboelectric Nanogenerators (TENGs)

2.1 Operating Mechanisms of TENGs

Based on the ideas of transforming mechanical energy into electricity, triboelectric nanogenerators (TENGs) can operate in four primary modes.

Vertical contact-separation mode

Vertical contact-separation mode, the most basic configuration, has two materials with varying triboelectric polarities come into contact, therefore causing charge transfer. Separation generates an electrical potential difference that pushes electrons across an outside circuit to offset the charge distribution[26].

The theoretical framework for contact-separation mode TENGs can be established using a capacitor model based on Maxwell's displacement current theory. The fundamental V-Q-X relationship governing the output characteristics is expressed as:

$$\mathrm{V} = -\frac{\mathrm{Q}}{\varepsilon_0 \mathrm{S}}(\mathrm{d}_0 + \mathrm{x(t)}) + \frac{\sigma}{\varepsilon_0}\mathrm{x(t)}$$

$$d_0 = \sum_{i=1}^{n} \frac{d_i}{\varepsilon_{ri}}$$

where V represents the voltage between electrodes, Q denotes the transferred charge, x(t) is the separation distance as a function of time, ε_0 is the vacuum permittivity, S is the contact area,d_0 is the sum of the products of each dielectric layer's thickness and the reciprocal of its relative permittivity, representing the equivalent dielectric thickness of the entire system, and σ represents the surface charge density[12].

Lateral sliding mode

Two parallel surfaces' relative sliding forms the basis of the lateral sliding mode. In this mode, the two surfaces move against each other in the same plane, generating electrical output. For a typical lateral sliding configuration, the V-Q-x relationship can be derived based on the parallel plate capacitor model:

$$\mathrm{V} = -\frac{1}{\mathrm{C}}\mathrm{Q} + V_{\mathrm{OC}} = -\frac{d_0}{\mathrm{w}\varepsilon_0(1-x)}\mathrm{Q} + \frac{\sigma d_0 x}{\varepsilon_0(1-x)}$$

where V is the voltage between electrodes, Q represents the transferred charge, S is the overlap area, d_0 is the effective dielectric thickness of the system, x is the sliding displacement, ε_0 is the vacuum permittivity,w is the width of the electrodes and σ is the surface charge density[12].

Single electrode mode

In single-electrode mode, TENG operates based on electrostatic induction between a moving object and a fixed electrode.In particular, this mode is very useful for sensing environments in which it is not possible to achieve direct electrical contact with both surfaces. The induced potential difference (V) is given by:

$$\mathrm{V} = \sigma\mathrm{S}\frac{\mathrm{C}_2}{\mathrm{C}_1\mathrm{C}_2 + \mathrm{C}_2\mathrm{C}_3 + \mathrm{C}_3\mathrm{C}_1}\left(1 - \frac{\mathrm{Q}}{\sigma\mathrm{S}}\left(1 + \frac{\mathrm{C}_1}{\mathrm{C}_2}\right)\right)$$

where σ is the surface charge density, S is the electrode area,C_1 ,C_2 andC_3 are the capacitances between different electrical nodes, and Q is the net charge transferred through the load[30].

Freestanding triboelectric-layer mode

In freestanding triboelectric layer mode, no direct contact is required at the electrodes, and there is a layer of dielectric at the two electrode sides that moves relative to the electrodes. In this configuration, there is minimal mechanical wear and high durability under harsh environmental conditions. This potential difference generated between the electrodes can be written as:

$$V = -\frac{1}{C}Q + V_{OC} = -\frac{d_0 + g}{\varepsilon_0 S}Q + \frac{2\sigma x}{\varepsilon_0}$$

where d_0 is the effective dielectric thickness, g is the air gap distance, ε_0 is the vacuum permittivity, S is the area of the electrode,σ is the triboelectric charge density, and x is the displacement of the freestanding layer [25].

Regarding environmental use, the benefits of each working mode of triboelectric nanogenerators (TENGs) change. Usually, the contact-separation mode provides great power density, which makes it appropriate for water treatment systems [17]. Its straightforward design, simple manufacturing, and low cost define this mode [20]. For ongoing air purification systems, the lateral sliding mode offers sustained output. This mode has demonstrated high efficiency and continuous high output for applications like reciprocation and rotation; it is especially effective for in-plane regular movement [22][27]. The single-electrode mode allows for easier device designs for environmental monitoring. Though it has less output performance due to the small charge transfer, this mode is the simplest in structure and hence very appropriate for self-powered uses [12]. Under severe environmental conditions, the freestanding mode guarantees a long operational life. Easily manufactured and incorporated into many real-time applications, this mode has shown great output efficiency and electrical output[12][25].

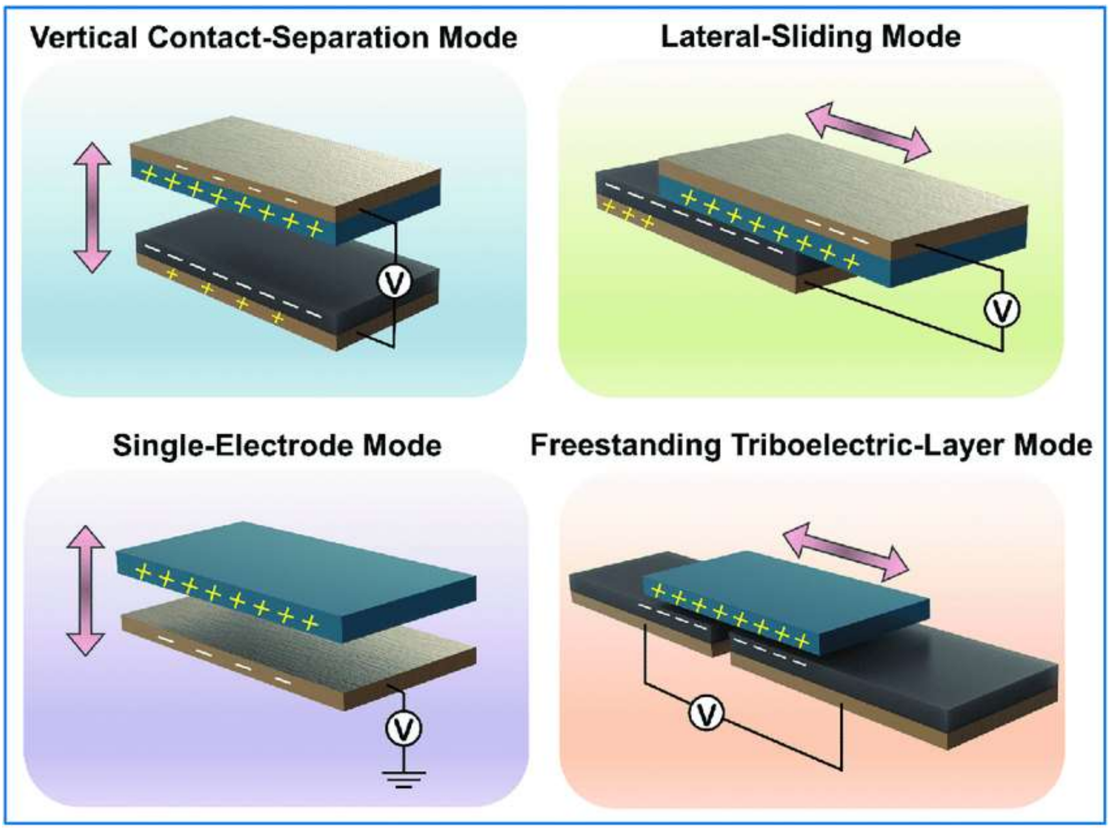

Figure 1. Four operational modes of TENGs: (a) vertical contact-separation mode, (b) lateral-sliding mode, (c) single electrode mode, and (d) freestanding triboelectric-layer mode[29].

2.2 Energy conversion mechanism

There are two steps in the conversion of mechanical energy to electrical energy provided by TENGs. Mechanical energy leads to contact between both triboelectric materials and, in turn, charge separation. Second, the separated charges establish an electric field to drive the electron flow through an external circuit and produce power suitable for use. The efficiency of this conversion is dependent on the surface roughness, contact area, and mechanical movement frequency [6].

2.3 Types of materials used in TENGs

The performance of TENGs is highly dependent on the selection of triboelectric materials for the construction of TENGs. These materials are ranked by their tendency to gain or lose electrons during contact or friction in the triboelectric series.Common materials include polymers such as polytetrafluoroethylene (PTFE), polyethylene terephthalate (PET), and various metals, each of which exhibit distinct triboelectric properties [7]. In addition, biopolymers have been explored as materials for TENGs, as they are renewable and biodegradable and fit with sustainability goals [21].

2.4 Significance of Material Selection and Structural Design

The performance of TENGs is significantly influenced by the structural design and material selection. While the energy conversion efficiency and structure durability are set by the structural configuration, materials define the triboelectric properties and charge transfer efficiency as well as environmental compatibility.

New materials have been made available for TENGs construction through advances in materials science. Figuratively showing this view, biopolymer-based TENGs (BP TENG) are both green and support sustainable development objectives. The use of nanomaterials (e.g., metal–organic frameworks (MOFs)) can help to promote charge transfer and dielectric properties which may improve overall performance[7].

Structurally speaking, multilayered designs enlarge the charge generation contact area, therefore greatly boosting the electrical output. Under a 30 N force at 1 Hz, for instance, the 3DW-TENG—which uses friction, spacer, and electrode layers—achieved an open-circuit voltage of 9.38 V, a short-circuit current of 31.65 nA, and a peak power density of 2.16×10^{-2} mW/m². Likewise, the RD-TENG, which employs multiphase coupling, produced an outstanding open-circuit voltage of 120 V and a short-circuit current density of 1.86 μA, therefore powering LEDs and offering corrosion protection[28].

Increasing energy output, lifetime, and adaptability depends on optimising TENG structures with multilayered designs and judiciously selected materials.These developments make TENGs more dependable for environmental and industrial use by addressing significant issues like low efficiency and poor stability.This method also lays the groundwork for the next generation of high-performance TENG technologies.

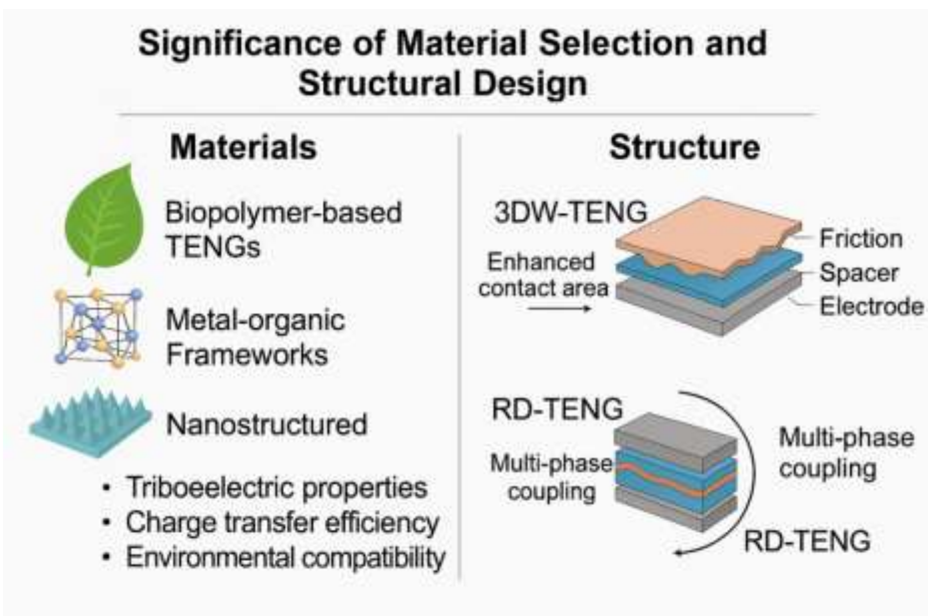

Figure 2: Importance of structural design and material choice. Schematic illustration of the material selection and structural design of TENGs. Their advantages in triboelectric properties, charge transition efficiency, and compatibility with the environment, three categories of materials, including biodegradable polymer based TENGs, metal-organic frameworks (MOFs), and nanostructured material, are illustrated on the left. On the right, various TENG structures are shown, including 3D TENG (3DW-TENG) and multiphase coupling TENG (RD-TENG), which can increase the contact area, energy conversion efficiency, and multiphase coupling**.**

3. Applications in Environmental Remediation

3.1 Water Treatment

Triboelectric nanogenerators (TENGs) are a new and promising technology among the various technologies used for water treatment because they can provide energy to electrochemical reactions that will degrade pollutants. The coupling of TENGs with electrochemical systems has greatly enhanced the degradation of organic pollutants, as well as the removal of heavy metals from aqueous solutions [9]. Huang et al. showed that, within three hours, TENGs led to 100% gold dissolution, which indicates their ability to recover metal from secondary resources, for example, electronic waste [3].

Recently, studies have been conducted to exploit TENGs for the electrochemical degradation of specific organic pollutants such as dyes and pharmaceuticals. For example, Shen et al. demonstrated enhanced performance when a triboelectric nanogenerator (TENG) was combined with a photocatalyst to degrade brilliant green dye. The degradation efficiency surpassed 88.26% within 40 minutes[16]. As a result, the self-powered nature of TENGs makes them a sustainable option for water purification.

In addition, TENGs have been used to remove heavy metals from wastewater. Su et al. employed an electric field to precipitate and remove heavy metals such as lead and cadmium through a TENG-driven electrochemical system. They also integrated TENGs with TiO_2 nanoparticles, which significantly accelerated the degradation of methyl orange (MO) compared with TENGs that were not used. With TENG assistance, 76% degradation was achieved within 120 minutes**,** whereas only 26% degradation occurred without TENGs. The primary reason for this improvement is the efficient separation and migration of charge carriers, which reduces recombination and enhances the overall degradation efficiency[9].

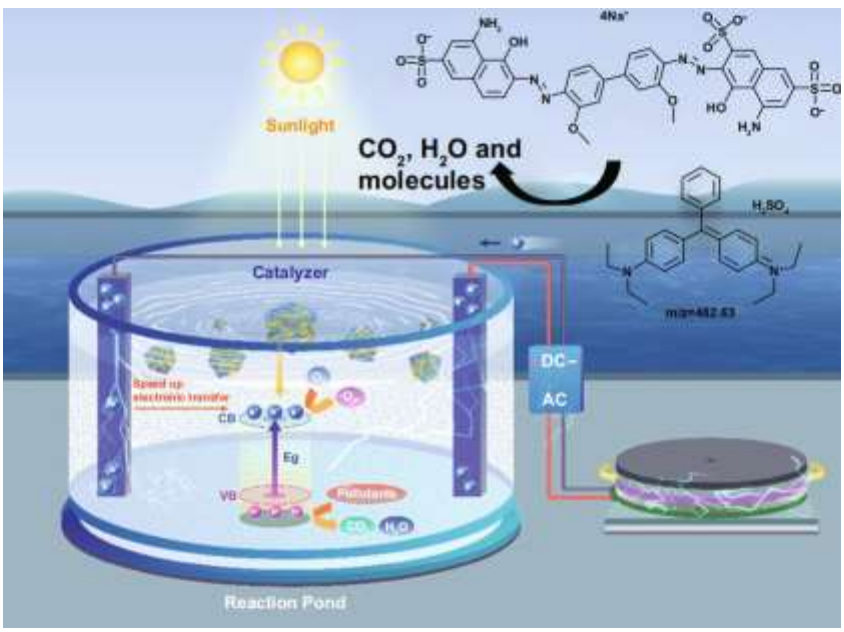

Figure 3. Solar-Powered Water Treatment with TENGs[16]. This illustration shows a system using a triboelectric nanogenerator (TENG) for solar-powered water purification.

3.2 Air Purification

Triboelectric nanogenerators (TENGs) being included into air purification has shown much promise. High-voltage power from TENGs can propel the photocatalytic breakdown of particulate matter and volatile organic compounds (VOCs). Xiaoliang Li and colleagues' findings indicate that this boosts the generation of reactive species including superoxide and hydroxyl radicals in photocatalysts. This approach increases the general efficiency of air purification systems and hastens the breakdown of contaminants. The incorporation of TENGs, Tesla valves and photocatalysis also aids in the optimising of the collision frequency between photocatalysts and air contaminants, therefore enhancing their removal[19].

Uses of TENGs go beyond the photocatalytic.Recent studies have sought to combine an ILP@MF with a low-voltage electrical field to enhance the particle capture efficiency. Though it removes PM2.5 as well as PM10 particles, the filter requires a commercial power supply, such as a silicon solar cell or a button lithium battery. The limitations of these external power sources dramatically limit the system's portability and self-sufficiency. Integrating these TENGs has the potential to solve these constraints with a self-powered device improving system efficiency and decreasing electrical dependence of outside power sources: This combination could enhance the flexibility and sustainable potential for the future studies of air purification technologies for the system[5].

Moreover, TENGs' environmental adaptability is appropriate for harsh industrial and urban settings. The creative coupling of TENGs with Tesla valve designs has recently enhanced VOC and particle removal by better optimising gas-photocatalyst interaction dynamics [19].

In terms of meeting the worldwide demand for low-carbon solutions, these developments position TENGs as a more sustainable choice than energy-intensive air purification technologies.

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Figure 4. Schematic diagrams of the electrostatic–photocatalytic air purification system. This system is inspired by the Tesla valve, which integrates both electrostatic fields and photocatalytic purification functions[19].

3.3 Soil Remediation

Soil remediation monitoring and treatment by triboelectric nanogenerators (TENGs) is promising as a sustainable technology. By using ambient mechanical energy, they are appropriate for self-sustained systems in environmental and agricultural uses. For instance, Luo et al. created an LPL-TENG that powers from plant leaves without influencing their growth. Detecting leaf humidity allows this device to monitor soil conditions remotely with a power density of 90.67 mW/m². Tracking changes in soil conditions with this type of real-time, low-power monitoring would be particularly useful in the context of soil remediation. This strategy provides a means to assist remedial activities independent of outside power sources[13].

Triboelectric nanogenerators (TENGs) also have the potential to enhance electrochemical treatment technologies for soil remediation in addition to monitoring. TENGs convert ambient mechanical energy into electrical power. This ability makes them a sustainable energy source for electrochemical applications, particularly in areas without standard electricity infrastructure. This capability ensures the promotion of the use of green energy and the feasibility of soil remediation in a variety of settings. However, the power output from TENGs for high-energy demand processes is constrained. These limitations and associated efficiency limitations can be addressed with hybrid systems that incorporate TENGs with other renewable energy sources [15].

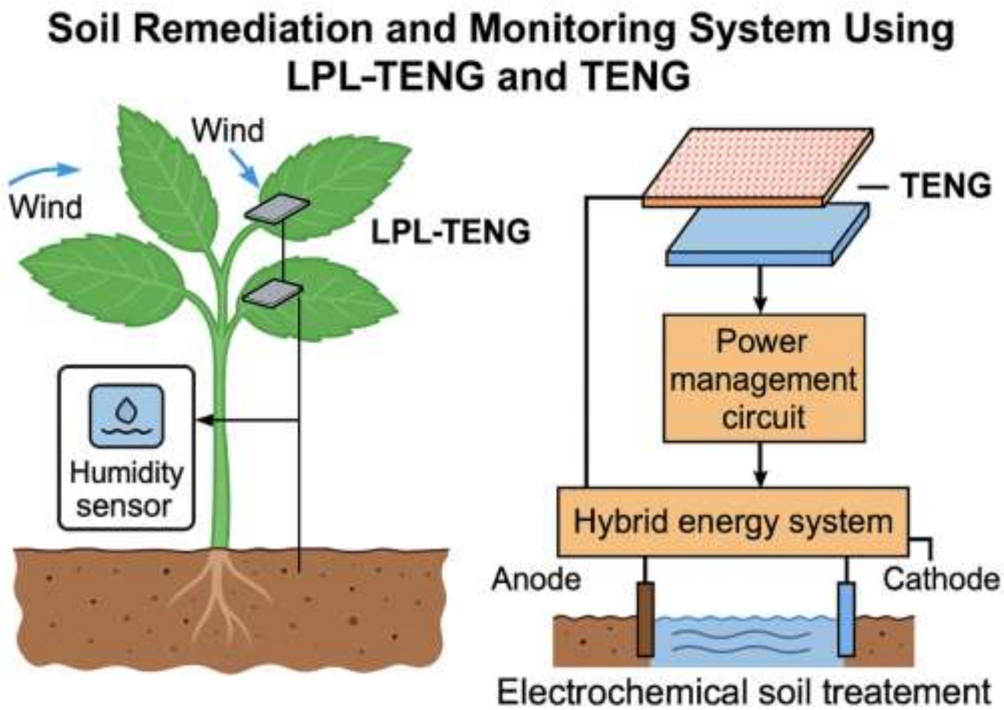

Figure 5. Schematic of the soil remediation and monitoring system using the LPL-TENG and TENG. This diagram shows how the LPL-TENG generates power from plant leaves to monitor humidity, and the TENG contributes to a hybrid energy system for sustainable electrochemical soil treatment.

3.4 Other Applications

TENGs have so far been applied for the remediation of contaminants in water, air, and soil, as well as to facilitate waste reuse and energy reclamation. Furthermore, TENGs could take mechanical energy from different sources to generate electricity and could also be applied as an economic remedy to environmental issues [10].

Energy harvesting from waste is very promising. Researchers utilize TENGs to capture electricity from mechanical motions (for example, the motion of waste particles in a landfill or the flow of wastewater in a treatment facility) using different mechanisms [1]. In these systems, electricity generation is used as a link to monitor and control waste treatment operations. This transforms waste, preventing it from harming the environment and instead producing a sustainable energy source. However, challenges remain for efficiency improvements, as well as the long-term reliability in rugged environments..

TENGs have also been looked at for generating renewable energy in coastal and offshore settings. TENGs can support present energy system and address waste and pollution issues by extracting energy from ocean sources—including waves and wind. For example, TENGs could be added to offshore wind turbines to capture more mechanical energy, so enabling alternative energy conversion and improving the efficiency of renewable energy systems. This integration thus presents problems. First, one must evaluate the cost and complexity of including TENGs into offshore wind turbines. To minimise the need for replacement and maintenance, TENGs have to be consistent and robust in harsh marine conditions. Given the fluctuating and erratic character of oceanic waves and wind, consistent energy generation is also challenging. Despite these obstacles, TENGs provide a promising technology to generate renewable energy and control environmental effects in the future [9].

TENGs have demonstrated extraordinary promise for application in the area of mechanochemistry to assist catalysis. TENGs, for instance, can increase the yield of mechanochemical reactions by up to 40% and help a more environmentally friendly approach with less energy needs compared to conventional techniques[23]. They can be scaled for industrial use and allow precise reaction control, therefore opening the path for sustainable catalysis.

4. Challenges and Future Directions of TENGs in Environmental Remediation

Triboelectric nanogenerators (TENGs) hold immense potential for environmental remediation because they convert mechanical energy into electricity. However, several challenges need to be addressed to make them more widely applicable.

4.1 Material Limitations and Performance Enhancement

The performance of TENGs significantly relies on the selection of triboelectric materials with high dielectric constants and suitable mechanical properties. Traditional materials often degrade over time and are not environmentally friendly. Recent advancements have focused on TENGs made from biopolymers (biopolymer TENGs or BP-TENGs), in which renewable, biodegradable TENG materials increase performance and sustainability [7].

4.2 Efficiency challenges in low-frequency environments

Low-frequency mechanical motion is widespread in many environments, influencing the power output of TENGs. TENGs typically perform best under high-frequency motion, which is often not achievable during real-world applications. This has led researchers to modify the structure of TENGs and use TENGs in hybrid systems to enable greater power output and broaden their applicability in real-world situations for applications such as monitoring pollutants and real-time monitoring of contaminants[9].

4.3 Scalability and Integration with Existing Infrastructure

Although TENGs are promising at the laboratory scale, large-area applications, including durable materials, economic materials, and existing infrastructures, face challenges in terms of scalability. Currently, researchers are investigating scalable, economically viable types of fabrication methods, such as the solvent-free particle rubbing assembly developed earlier this year [24].

4.4 Smart System Integration and Autonomous Monitoring

The integration of TENGs with smart technologies such as the Internet of Things (IoT) and artificial intelligence (AI) opens new possibilities for self-powered, autonomous environmental monitoring systems. For example, Li et al. developed TENG-based electrochemical systems integrated with the IoT for real-time environmental monitoring [8]. These technologies are already being used in agriculture to monitor soil health and water conditions, improving resource management [14]. Underwater, TENG-powered sensors extract energy from water flow to monitor water quality and environmental conditions in real time [11]. Furthermore, Vivekananthan et al.discussed the advantages of TENGs in portable and wearable devices that can enhance energy harvesting from daily activities, further contributing to smart system integration[20].

4.5 Sustainability and eco-friendly solutions

One such role implies the sustainability of TENGs in environmental remediation. They can convert mechanical energy from ambient sources to electricity and, thus, replace conventional energy infrastructures to promote circular economies. Epoxidized soybean oil-based polymers and other new biodegradable materials have decreased the environmental footprint of TENGs even further while maintaining high electrical performance and thermal stability [18].

4.6 Future Perspectives

The future of TENGs in environmental remediation is promising. With advances in materials science, TENGs are expected to become more efficient, affordable, and scalable [7]. The interdisciplinary collaboration of materials scientists, engineers, and environmental scientists will lead to innovations that allow TENGs to address increasingly complex environmental issues [9]. TENGs that are integrated with the IoT, AI, and other emerging technologies will also provide new opportunities for monitoring environmental issues, sustainable agriculture, and industrial waste [11][14].

5. Conclusion

Triboelectric nanogenerators (TENGs), because of their capability to convert mechanical energy into electricity, have revolutionized environmental remediation, as they mark the beginning of sustainable and self-powered solutions to major problems worldwide. Thus, these TENGs have potential applications in the degradation of pollutants with resource recovery and energy generation, which are in alignment with the principles of circular economy. Due to their flexibility and adaptability, TENGs hold potential as a sustainable substitute to ubiquitous energy-consuming techniques, particularly in fields like wastewater treatment, air purification and toxic waste disposal.

Furthermore, coupling TENGs with advanced electrochemistry techniques and novel materials has promoted enhanced environmental applications. Nevertheless, there exist problems concerning the optimization of the energy conversion efficiency, the enhancement of operational stability and the scaling up of production in situ. The future research areas of TENGs would focus on optimizing the TENGs architecture with novel eco-friendly materials combined with smart system design for addressing particular environmental related issues.

In general, the TENG technology marks a significant departure from sustainable environmental practices by offering the dual advantage of remediating the environment while simultaneously generating a useful form of energy. By overcoming existing constraints and leveraging its unique instruments, TENGs can prove instrumental in moving the world toward environmentally sustainable and resource efficient development..

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